Semantic Analysis

CSE 307 – Principles of Programming Languages

Slides courtesy:

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Role of Semantic Analysis

- Syntax vs. Semantics:
  - syntax concerns the ***form*** of a valid program (described conveniently by a context-free grammar CFG)
  - semantics concerns its ***meaning***: rules that go beyond mere form (e.g., the number of arguments contained in a call to a subroutine matches the number of formal parameters in the subroutine definition):
    - Defines what the program means
    - Detects if the program is correct
    - Helps to translate it into another representation

Role of Semantic Analysis

- Following parsing, the next two phases of the "typical" compiler are:
  - semantic analysis
  - (intermediate) code generation
- Semantic rules are divided into:
  - ***static*** semantics enforced at compile time
  - ***dynamic*** semantics: the compiler generates code to enforce dynamic semantic rules at run time (or calls libraries to do it) (for errors like division by zero, out-of-bounds index in array)
- The principal job of the ***semantic analyzer*** is to enforce static semantic rules, plus:
  - constructs a syntax tree
  - information gathered is needed by the code generator

Role of Semantic Analysis

- Parsing, semantic analysis, and intermediate code generation are interleaved:
  - a common approach interleaves parsing construction of a syntax tree with phases for semantic analysis and code generation
  - The semantic analysis and intermediate code generation <u>**annotate**</u> the parse tree with ***attributes***
    - ***Attribute grammars*** provide a formal framework for the decoration of a syntax tree
    - The ***attribute flow*** constrains the order(s) in which nodes of a tree can be decorated.
      - replaces the parse tree with a syntax tree that reflects the input program in a more straightforward way

Role of Semantic Analysis

- Dynamic checks: semantic rules enforced at run time
  - C requires no dynamic checks at all (it relies on the hardware to find division by zero, or attempted access to memory outside the bounds of the program).
  - Java check as many rules as possible, so that an untrusted program cannot do anything to damage the memory or files of the machine on which it runs.
- Many compilers that generate code for dynamic checks provide the option of disabling them (enabled during program development and testing, but disables for production use, to increase execution speed)
  - Hoare: "*like wearing a life jacket on land, and taking it off at sea*"

Role of Semantic Analysis

- ***Assertions***: logical formulas written by the programmers regarding the values of program data used to reason about the correctness of their algorithms (the assertion is expected to be **`true`** when execution reaches a certain point in the code):
  - Java: **`assert denominator != 0;`**
    - An **`AssertionError`** exception will be thrown if the semantic check fails at run time.
  - C: **`assert(denominator != 0);`**
    - If the assertion fails, the program will terminate abruptly with a message: **`a.c:10: failed assertion 'denominator != 0'`**
  - Some languages also provide explicit support for ***invariants*, preconditions, and post-conditions**.
    - Like Dafny from Microsoft https://github.com/Microsoft/dafny

Java Assertions

- Java example:
  - An assertion in Java is a statement that enables us to assert an assumption about our program.
  - An assertion contains a Boolean expression that should be true during program execution.
  - Assertions can be used to assure program correctness and avoid logic errors.
  - An assertion is declared using the Java keyword **`assert`** in JDK 1.5 as follows:

```
assert assertion; //OR
assert assertion : detailMessage;
```

where **`assertion`** is a Boolean expression and **`detailMessage`** is a primitive-type or an **`Object`** value.

Java Assertion Example

```
public class AssertionDemo {
  public static void main(String[] args) {
    int i;
    int sum = 0;
    for (i = 0; i < 10; i++) {
      sum += i;
    }
    assert i==10;
    assert sum>10 && sum<5*10 : "sum is " + sum;
  }
}
```

- When an assertion statement is executed, Java evaluates the assertion
  - If it is false, an **`AssertionError`** will be thrown

Java Assertion Example

- The **`AssertionError`** class has a no-arg constructor and seven overloaded single-argument constructors of type **`int`**, **`long`**, **`float`**, **`double`**, **`boolean`**, **`char`**, and **`Object`**
  - For the first assert statement in the example (with no detail message), the no-arg constructor of **`AssertionError`** is used.
  - For the second assert statement with a detail message, an appropriate **`AssertionError`** constructor is used to match the data type of the message.
  - Since **`AssertionError`** is a subclass of **`Error`**, when an assertion becomes false, the program displays a message on the console and exits

Running Programs with Assertions

- By default, the assertions are disabled at runtime
  - To enable it, use the switch **-enableassertions**, or **-ea** for short, as follows:

```
java -ea AssertionDemo
    public class AssertionDemo {
       public static void main(String[] args){
          int i; int sum = 0;
          for (i = 0; i < 10; i++) {
             sum += i;
          }
          assert i!=10;
       }
    }
Exception in thread "main" java.lang.AssertionError
at AssertionDemo.main(AssertionDemo.java:7)
```

Running Programs with Assertions

- Assertions can be selectively enabled or disabled at class level or package level
  - The disable switch is **`-disableassertions`** or **`-da`** for short.
  - For example, the following command enables assertions in package **`package1`** and disables assertions in class **`Class1`**:

```
java -ea:package1 -da:Class1 AssertionDemo
```

Using Exception Handling or Assertions?

- Assertion should not be used to replace exception handling.
  - Exception handling deals with unusual circumstances during program execution.
  - Assertions are to assure the correctness of the program
  - Exception handling addresses ***robustness*** and assertion addresses ***correctness***
  - Assertions are used for internal consistency and validity checks
  - Assertions are checked at runtime and can be turned on or off at startup time

Using Exception Handling or Assertions?

- Do not use assertions for argument checking in public methods:
  - Valid arguments that may be passed to a public method are considered to be part of the method's contract
  - The contract must always be obeyed whether assertions are enabled or disabled
    - For example, the following code in the **`Circle`** class should be rewritten using exception handling:

```
public void setRadius(double newRadius) {
  assert newRadius >= 0;
  radius =  newRadius;
}
```

Using Exception Handling or Assertions?

- Use assertions to reaffirm assumptions.
  - This gives you more confidence to assure correctness of the program.
  - A common use of assertions is to replace assumptions with assertions in the code.
  - A good use of assertions is place assertions in a switch statement without a default case. For example:

```
switch (month) {
  case 1: ... ; break;
  case 2: ... ; break;
  ...
  case 12: ... ; break;
  default: assert false : "Invalid month: " + month;
}
```

Correctness of Algorithms

- **Loop *Invariants*:** used to prove correctness of a loop with respect to pre- and post-conditions

  [Pre-condition for the loop]

  while (G)

  [Statements in the body of the loop]

  end while

  [Post-condition for the loop]

A loop is correct with respect to its pre- and post-conditions if, and only if, whenever the algorithm variables satisfy the pre-condition for the loop and the loop terminates after a finite number of steps, the algorithm variables satisfy the post-condition for the loop

Loop Invariant

- A **loop invariant I(n)** is a predicate with domain a set of integers, which for each iteration of the loop **(mathematical induction)**, if the predicate is true before the iteration, the it is true after the iteration

If **the loop invariant I(0) is true before the first iteration of the loop** **AND**

After a finite number of iterations of the loop, the guard G becomes false **AND**

The truth of **the loop invariant ensures the truth of the post-condition of the loop**

then the loop will be correct with respect to it pre- and post-conditions

Loop Invariant

- **Correctness of a Loop to Compute a Product:**

A loop to compute the product mx for a nonnegative integer m and a real number x, without using multiplication

[Pre-condition: m is a nonnegative integer, x is a real number, i = 0, and product = 0]

while (i $\neq$ m)

    product := product + x

    i := i + 1

end while

[Post-condition: product = mx]

Loop invariant I(n): i = n and product = n*x

Guard G: i $\neq$ m

Static analysis

- Static analysis: compile-time algorithms that predict run-time behavior
  - **Type checking**, for example, is static and precise in ML: the compiler ensures that no variable will ever be used at run time in a way that is inappropriate for its type
    - By contrast, languages like Lisp and Smalltalk accept the run-time overhead of dynamic type checks
  - In Java, type checking is mostly static, but dynamically loaded classes and type casts require run-time checks
- Static analysis is usually done for **Optimizations**
  - Optimizations can lead to security risks if implemented incorrectly (see 2018 Spectre hardware vulnerability: microarchitecture-level optimizations to code execution [can] leak information)

Attribute Grammars

- Both semantic analysis and (intermediate) code generation can be described in terms of ***annotation***, or "***decoration***" of a parse or syntax tree
  - attributes are properties/actions attached to the production rules of a grammar
  - ATTRIBUTE GRAMMARS provide a formal framework for decorating a parse tree

Attribute Grammars

- LR (bottom-up) grammar for arithmetic expressions made of constants, with precedence and associativity
  - detects of a string follows the grammar
  - but says nothing about what the program MEANS

$$
\begin{aligned}
E &\longrightarrow E \texttt{ + } T \\
E &\longrightarrow E \texttt{ - } T \\
E &\longrightarrow T \\
T &\longrightarrow T \texttt{ * } F \\
T &\longrightarrow T \texttt{ / } F \\
T &\longrightarrow F \\
F &\longrightarrow \texttt{- } F \\
F &\longrightarrow \texttt{(} E \texttt{)} \\
F &\longrightarrow \texttt{const}
\end{aligned}
$$

Attribute Grammars

semantic function (sum, etc.)

- **<u>Attributed grammar</u>**:
  - defines the semantics of the input program
    - <u>Associates expressions to mathematical concepts!!!</u>
  - Attribute rules are definitions, not assignments: they are not necessarily meant to be evaluated at any particular time, or in any particular order

$E_1 \longrightarrow E_2 \; \texttt{+} \; T$

$\quad \triangleright$ E_1.val := sum(E_2.val, T.val)

$E_1 \longrightarrow E_2 \; \texttt{-} \; T$

$\quad \triangleright$ E_1.val := difference(E_2.val, T.val)

$E \longrightarrow T$

$\quad \triangleright$ E.val := T.val *copy rule*

$T_1 \longrightarrow T_2 \; \texttt{*} \; F$

$\quad \triangleright$ T_1.val := product(T_2.val, F.val)

$T_1 \longrightarrow T_2 \; \texttt{/} \; F$

$\quad \triangleright$ T_1.val := quotient(T_2.val, F.val)

$T \longrightarrow F$

$\quad \triangleright$ T.val := F.val

$F_1 \longrightarrow \texttt{-} \; F_2$

$\quad \triangleright$ F_1.val := additive_inverse(F_2.val)

$F \longrightarrow \texttt{(} \; E \; \texttt{)}$

$\quad \triangleright$ F.val := E.val

$F \longrightarrow \texttt{const}$

$\quad \triangleright$ F.val := const.val

Attribute Grammars

- Attributed grammar to count the elements of a list:

$$L \longrightarrow \texttt{id}$$

$$L_1 \longrightarrow L_2 \;,\; \texttt{id}$$

$\triangleright$ $L_1.c := 1$

$\triangleright$ $L_1.c := L_2.c + 1$

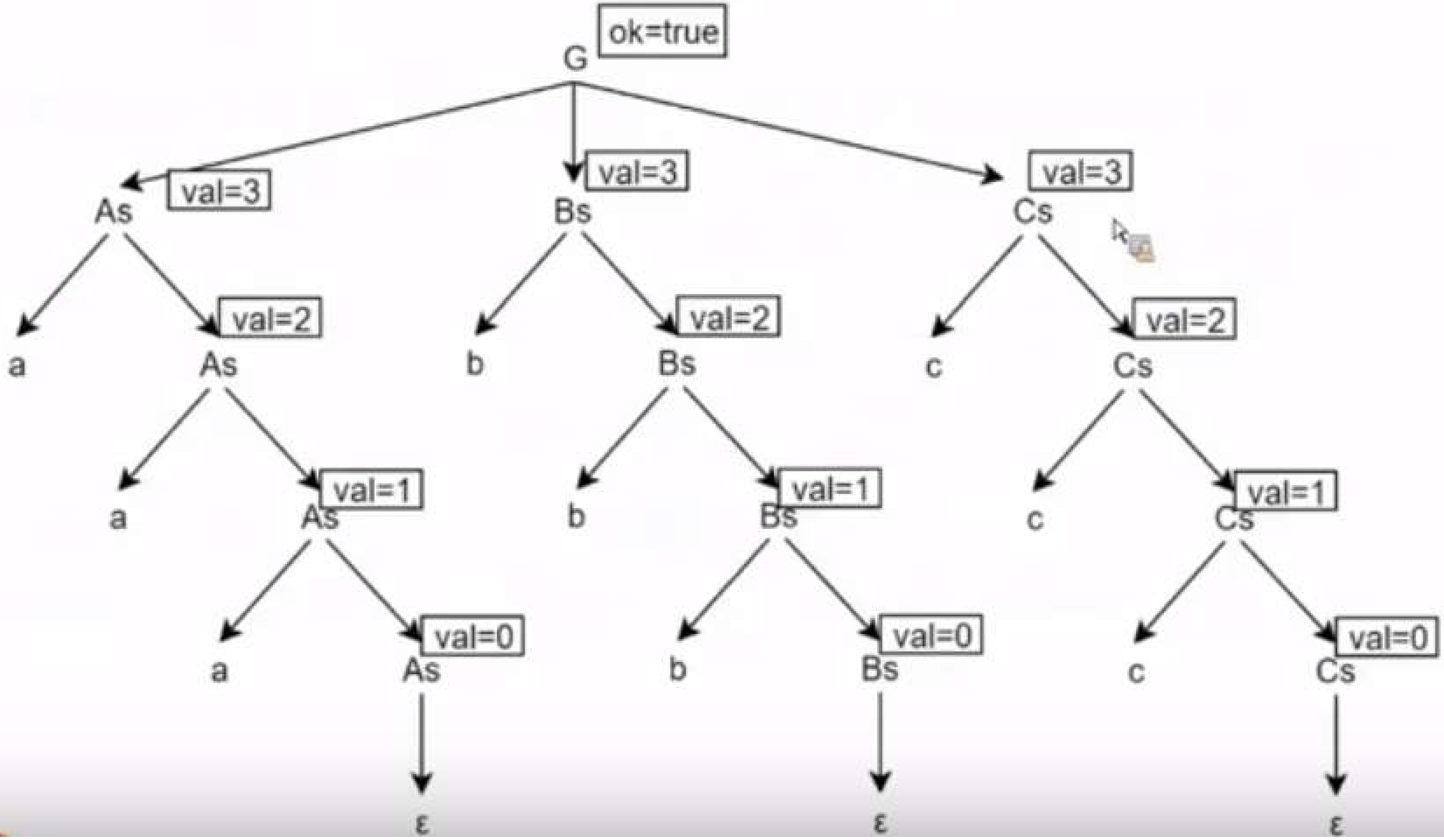
More than just CFG

- The language L = $a^n b^n c^n$ (e.g., *abc*, *aabbcc*, *aaabbbccc*,…) is not context free
- It can be captured, however, using an attribute grammar:

```
G → As Bs Cs ▷ G.ok := (As.val == Bs.val
                        ∧ Bs.val == Cs.val)
As1 → a As2   ▷ As1.val := As2.val + 1
As  → ε       ▷ As.val := 0
Bs1 → b Bs2   ▷ Bs1.val := Bs2.val + 1
Bs  → ε       ▷ Bs.val := 0
Cs1 → c Cs2   ▷ Cs1.val := Cs2.val + 1
Cs  → ε       ▷ Cs.val := 0
```

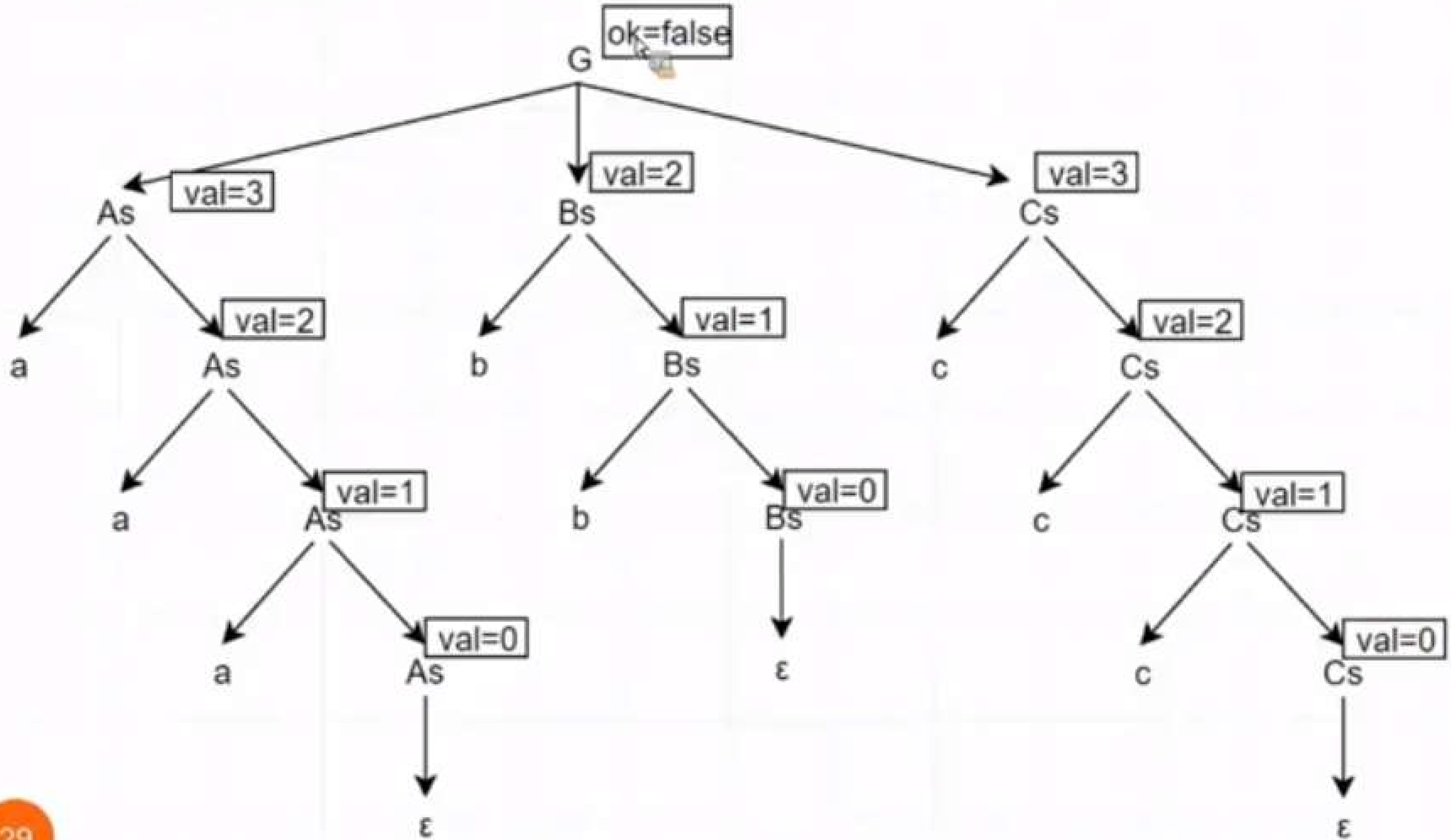
More than just CFG

- Annotate tree for "**aaabbbaaa**":



More than just CFG

- Annotate tree for "**aaabbaaa**":



Evaluating Attributes

- ***Synthesized Attributes***:
  - Data flows bottom-up
  - Can be parsed by LR grammars
  - LR parser: begin at the target string and try to arrive back at the start symbol
- ***Inherited Attributes***:
  - Data flows top-down and bottom-up
  - Can be parsed with LL grammars
  - LL parser: Begin at the start symbol and try to apply productions to arrive at target string

LL Parser

During an LL parse, the parser continuously chooses between two actions:

1. **Predict**: Based on the leftmost nonterminal and some number of lookahead tokens, choose which production ought to be applied to get closer to the input string.
2. **Match**: Match the leftmost guessed terminal symbol with the leftmost unconsumed symbol of input.

As an example, given this grammar:

- S → E
- E → T + E
- E → T
- T → `int`

Then given the string `int + int + int`, an LL(2) parser (which uses two tokens of lookahead) would parse the string as follows:

```
Production          Input               Action
---------------------------------------------------------
S                   int + int + int     Predict S -> E
E                   int + int + int     Predict E -> T + E
T + E               int + int + int     Predict T -> int
int + E             int + int + int     Match int
+ E                 + int + int         Match +
E                   int + int           Predict E -> T + E
T + E               int + int           Predict T -> int
int + E             int + int           Match int
+ E                 + int               Match +
E                   int                 Predict E -> T
T                   int                 Predict T -> int
int                 int                 Match int
                                        Accept
```

Notice that in each step we look at the leftmost symbol in our production. If it's a terminal, we match it, and if it's a nonterminal, we predict what it's going to be by choosing one of the rules.

- Explanatory video: https://www.tutorialspoint.com/compiler_design/ll_k_grammar.asp

LR Parser

In an LR parser, there are two actions:

1. **Shift**: Add the next token of input to a buffer for consideration.
2. **Reduce**: Reduce a collection of terminals and nonterminals in this buffer back to some nonterminal by reversing a production.

As an example, an LR(1) parser (with one token of lookahead) might parse that same string as follows:

```
Workspace         Input              Action
---------------------------------------------------------
                  int + int + int    Shift
int               + int + int        Reduce T -> int
T                 + int + int        Shift
T +               int + int          Shift
T + int           + int              Reduce T -> int
T + T             + int              Shift
T + T +           int                Shift
T + T + int                          Reduce T -> int
T + T + T                            Reduce E -> T
T + T + E                            Reduce E -> T + E
T + E                                Reduce E -> T + E
E                                    Reduce S -> E
S                                    Accept
```

As an example, given this grammar:

- S → E
- E → T + E
- E → T
- T → `int`

Then given the string `int + int + int`

- Additional videos on parsing (recommended):
- https://www.tutorialspoint.com/compiler_design/slr_parser_parsing_an_input_string.asp

Attribute Grammars Example with variables

```
Tokens: int (attr val), var (attr name)

S -> var = E
        ▷ assign(var.name, E.val)
E1 -> E2 + T
        ▷ E1.val = sum(E2.val, T.val)
E1 -> E2 - T
        ▷ E1.val = sub(E2.val, T.val)
E -> T
        ▷ E.val = T.val
T -> var
        ▷ T.val = lookup(var.name)
T -> int
        ▷ T.val = int.val
```

Evaluating Attributes

- The process of evaluating attributes is called ***annotation***, or ***DECORATION***, of the parse tree
  - When the parse tree under the previous example grammar is fully decorated, the value of the expression will be in the **`val`** attribute of the root
- The code fragments for the rules are called ***SEMANTIC FUNCTIONS***
  - For example:

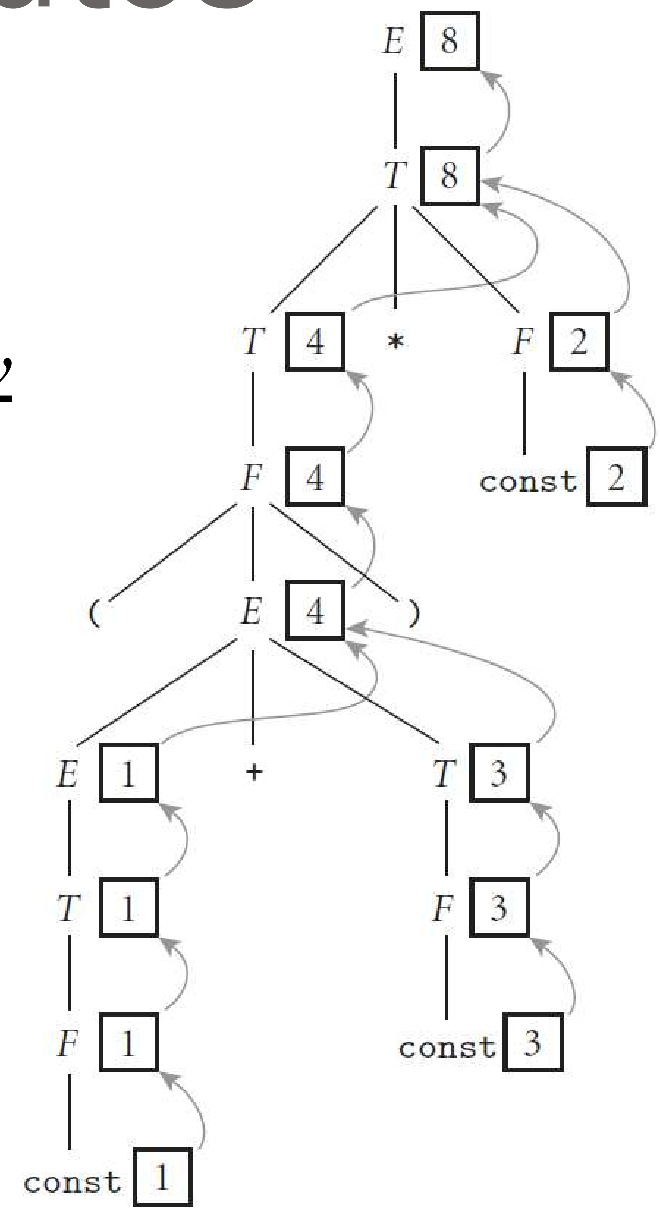
```
E1.val = sum(E2.val, T.val)
```

  - Semantic functions are not allowed to refer to any variables or attributes outside the current production

Evaluating Attributes

Decoration of a parse tree for (1 + 3) * 2 needs to detect the order of attribute evaluation:

- Curving arrows show the ***attribute flow***
  - Each box holds the output of a single semantic rule
  - The arrow is the input to the rule
- ***synthesized attributes***: their values are calculated (synthesized) only in productions in which their symbol appears on the left-hand side.
- A ***S-attributed grammar*** is a grammar where all attributes are synthesized.

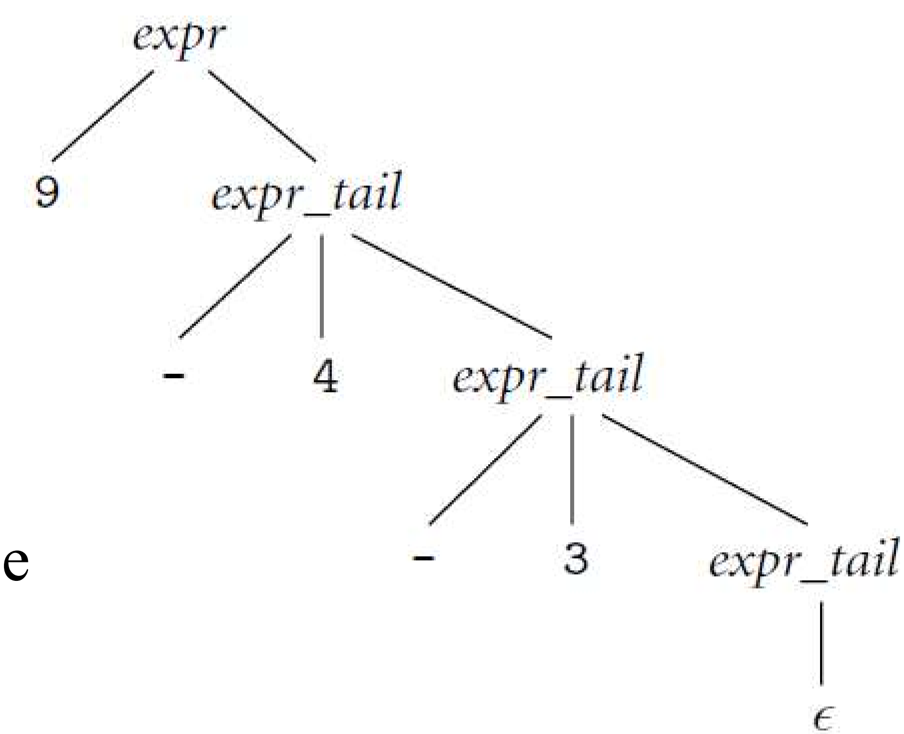


Evaluating Attributes

- Tokens have only synthesized attributes, initialized by the scanner (name of an identifier, value of a constant, etc.).
- ***INHERITED attributes*** may depend on things above or to the side of them in the parse tree:

$$expr \longrightarrow \texttt{const}\ \ expr\_tail$$

$$expr\_tail \longrightarrow \texttt{-}\ \texttt{const}\ \ expr\_tail \mid \epsilon$$

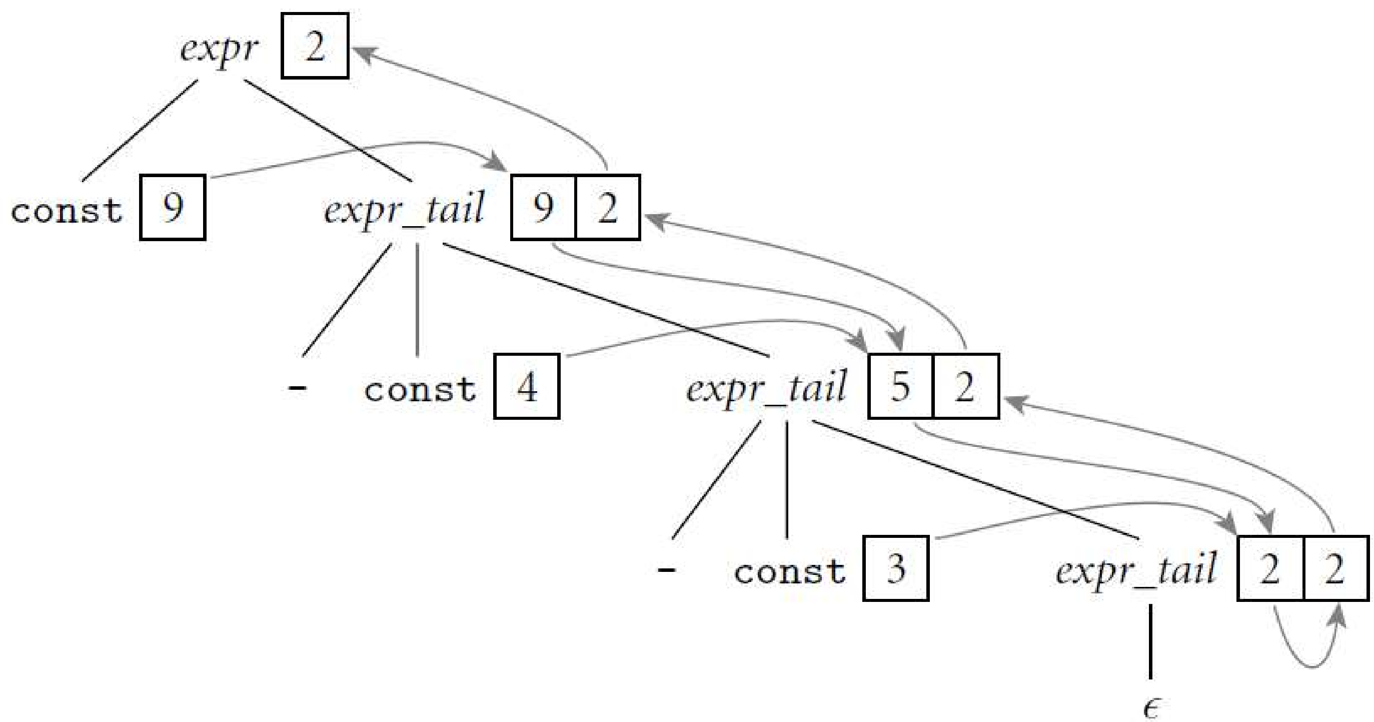


we cannot summarize the right subtree of the root with a single numeric value

subtraction is left associative: requires us to embed the entire tree into the attributes of a single node

Evaluating Attributes

- Decoration with ***left-to-right attribute flow***: pass attribute values not only **bottom-up** but **also left-to-right** in the tree
  - 9 can be combined in left-associative fashion with the 4 and
  - 5 can then be passed into the middle *expr_tail* node, combined with the 3 to make 2, and then passed upward to the root

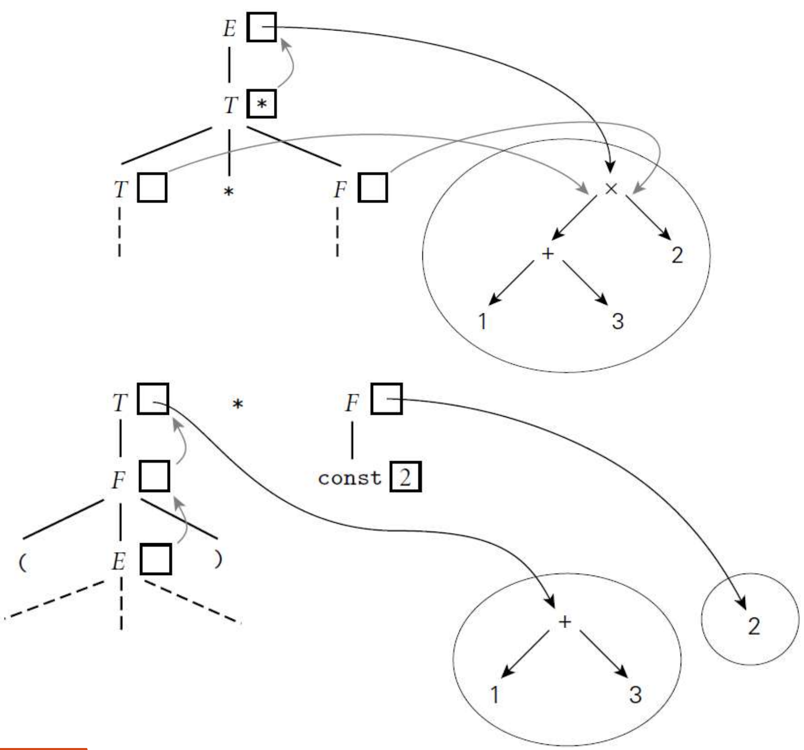


Syntax trees

- A ***one-pass compiler*** is a compiler that interleaves semantic analysis and code generation with parsing
- ***Syntax trees***: if the parsing and code generation are **not interleaved**, then attribute rules must be added to create the syntax tree:
  - The attributes in these grammars point to nodes of the syntax tree (containing unary or binary operators, pointers to the supplied operand(s), etc.)
  - The attributes hold neither numeric values nor target code fragments
- https://www.youtube.com/watch?v=u4vBsGphFAU

Syntax trees

- Bottom-up (S-attributed) attribute grammar to construct a syntax tree
- S-attributed: every attribute is synthesized



$E_1 \longrightarrow E_2 + T$
▷ E_1.ptr := make_bin_op("+", E_2.ptr, T.ptr)

$E_1 \longrightarrow E_2 - T$
▷ E_1.ptr := make_bin_op("−", E_2.ptr, T.ptr)

$E \longrightarrow T$
▷ E.ptr := T.ptr

$T_1 \longrightarrow T_2 * F$
▷ T_1.ptr := make_bin_op("×", T_2.ptr, F.ptr)

$T_1 \longrightarrow T_2 \, / \, F$
▷ T_1.ptr := make_bin_op("÷", T_2.ptr, F.ptr)

$T \longrightarrow F$
▷ T.ptr := F.ptr

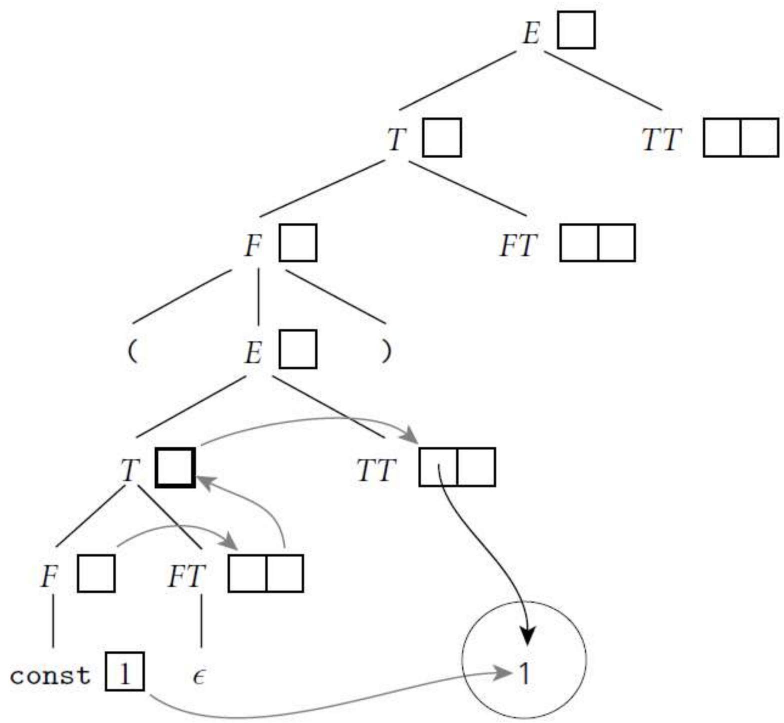
$F_1 \longrightarrow - F_2$
▷ F_1.ptr := make_un_op("+/_", F_2.ptr)

$F \longrightarrow (E)$
▷ F.ptr := E.ptr

$F \longrightarrow$ const
▷ F.ptr := make_leaf(const.val)

Syntax trees

- Top-down (L-attributed) attribute grammar to construct a syntax tree:
- L-attributed: Synthesized or inherited attributes



$E \longrightarrow T\ TT$
- $\triangleright$ TT.st := T.ptr
- $\triangleright$ E.ptr := TT.ptr

$TT_1 \longrightarrow +\ T\ TT_2$
- $\triangleright$ TT_2.st := make_bin_op("+", TT_1.st, T.ptr)
- $\triangleright$ TT_1.ptr := TT_2.ptr

$TT_1 \longrightarrow -\ T\ TT_2$
- $\triangleright$ TT_2.st := make_bin_op("−", TT_1.st, T.ptr)
- $\triangleright$ TT_1.ptr := TT_2.ptr

$TT \longrightarrow \epsilon$
- $\triangleright$ TT.ptr := TT.st

$T \longrightarrow F\ FT$
- $\triangleright$ FT.st := F.ptr
- $\triangleright$ T.ptr := FT.ptr

$FT_1 \longrightarrow *\ F\ FT_2$
- $\triangleright$ FT_2.st := make_bin_op("×", FT_1.st, F.ptr)
- $\triangleright$ FT_1.ptr := FT_2.ptr

$FT_1 \longrightarrow /\ F\ FT_2$
- $\triangleright$ FT_2.st := make_bin_op("÷", FT_1.st, F.ptr)
- $\triangleright$ FT_1.ptr := FT_2.ptr

$FT \longrightarrow \epsilon$
- $\triangleright$ FT.ptr := FT.st

$F_1 \longrightarrow -\ F_2$
- $\triangleright$ F_1.ptr := make_un_op("+/_", F_2.ptr)

$F \longrightarrow (\ E\ )$
- $\triangleright$ F.ptr := E.ptr

$F \longrightarrow$ const
- $\triangleright$ F.ptr := make_leaf(const.val)

Action Routines

- While it is possible to construct automatic tools to analyze attribute flow and decorate parse trees, most compilers rely on ***action routines***, which the compiler writer embeds in the right-hand sides of productions to evaluate attribute rules at **specific points in a parse**
  - An ***action routine*** is like a "*semantic function*" that we tell the compiler to execute at a particular point in the parse
    - In an LL-family parser, action routines can be embedded at arbitrary points in a production's right-hand side
      - They will be executed left to right during parsing

Action Routines

- If semantic analysis and code generation are interleaved with parsing, then action routines can be used to perform semantic checks and generate code
  - Later compilation phases can then consist of ad-hoc tree traversal(s), or can use an automatic tool to generate a translation scheme
- If semantic analysis and code generation are broken out as separate phases, then action routines can be used to build a syntax tree

Action Routines

- Entries in the attributes stack are pushed and popped automatically
  - The *syntax tree* is produced

$program \longrightarrow item$

$int\_decl : item \longrightarrow id\ item$

$read : item \longrightarrow id\ item$

$real\_decl : item \longrightarrow id\ item$

$write : item \longrightarrow expr\ item$

$null : item \longrightarrow \epsilon$

$\text{‘}\div\text{’} : expr \longrightarrow expr\ expr$

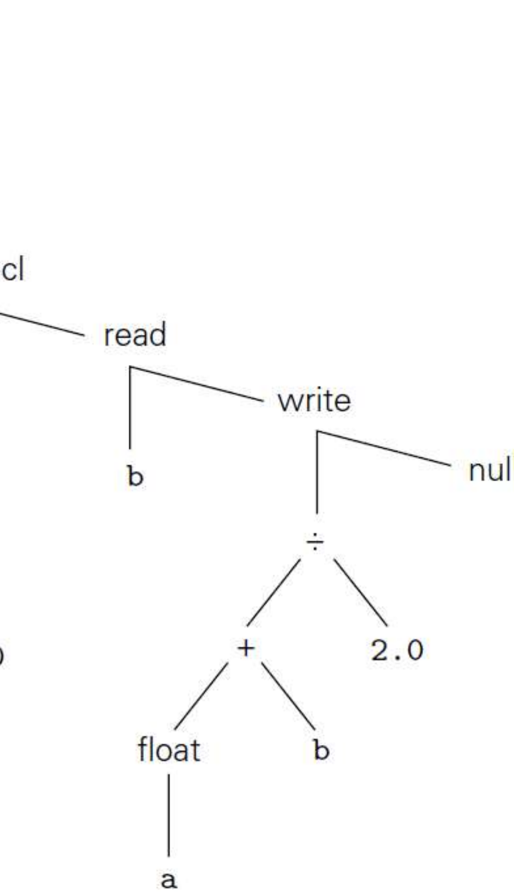
$\text{‘}+\text{’} : expr \longrightarrow expr\ expr$

$float : expr \longrightarrow expr$

$id : expr \longrightarrow \epsilon$

$real\_const : expr \longrightarrow \epsilon$

```
int a
read a
real b
read b
write (float (a) + b) / 2.0
```



Decorating a Syntax Tree

- Sample of complete tree grammar representing structure of the syntax tree

$id : expr \longrightarrow \epsilon$

▷ if (id.name, A) ∈ expr.symtab -- for some type A
  expr.errors := null
  expr.type := A
else
  expr.errors := [id.name "undefined at" id.location]
  expr.type := error

$int\_const : expr \longrightarrow \epsilon$

▷ expr.type := int

$real\_const : expr \longrightarrow \epsilon$

▷ expr.type := real

$`+' : expr_1 \longrightarrow expr_2 \; expr_3$

▷ $expr_2$.symtab := $expr_1$.symtab
▷ $expr_3$.symtab := $expr_1$.symtab
▷ check_types($expr_1$, $expr_2$, $expr_3$)

$`-' : expr_1 \longrightarrow expr_2 \; expr_3$

▷ $expr_2$.symtab := $expr_1$.symtab
▷ $expr_3$.symtab := $expr_1$.symtab
▷ check_types($expr_1$, $expr_2$, $expr_3$)

$`\times' : expr_1 \longrightarrow expr_2 \; expr_3$

▷ $expr_2$.symtab := $expr_1$.symtab
▷ $expr_3$.symtab := $expr_1$.symtab
▷ check_types($expr_1$, $expr_2$, $expr_3$)

$`\div' : expr_1 \longrightarrow expr_2 \; expr_3$

▷ $expr_2$.symtab := $expr_1$.symtab
▷ $expr_3$.symtab := $expr_1$.symtab
▷ check_types($expr_1$, $expr_2$, $expr_3$)

$float : expr_1 \longrightarrow expr_2$

▷ $expr_2$.symtab := $expr_1$.symtab
▷ convert_type($expr_2$, $expr_1$, int, real, "float of non-int")

$trunc : expr_1 \longrightarrow expr_2$

▷ $expr_2$.symtab := $expr_1$.symtab
▷ convert_type($expr_2$, $expr_1$, real, int, "trunc of non-real")