Short-Circuit Evaluation

- A **short-circuit evaluation** of an expression is one in which the result is determined without evaluating all of the operands and/or operators
  - Consider `(a < b) && (b < c)`:
    - If `a >= b`, there is no point evaluating `b < c` because `(a < b) && (b < c)` is automatically false
- (x && y) ≡ if x then y else false
- (x || y) ≡ if x then true else y

Short-Circuit Evaluation

- Short-circuit evaluation may lead to unexpected side effects and cause error
  - E.g., (a > b) || ((b++) / 3)
- C, C++, and Java:
  - Use short-circuit evaluation for Boolean operations (&& and ||)
  - Also provide bitwise operators that are **not short circuit** (& and |)

Short-Circuit Evaluation

- Ada: programmers can specify either

Non-SC eval	SC eval
(x or y)	(x or else y)
(x and y)	(x and then y)

Control Structures

- Selection
- Iteration
  - Iterators
- Recursion
- Concurrency & non-determinism
  - Guarded commands

Iteration Based on Data Structures

- A data-based iteration statement uses a user-defined data structure and a user-defined function to go through the structure's elements
  - The function is called an **iterator**
  - The iterator is invoked at the beginning of each iteration
  - Each time it is invoked, an element from the data structure is returned
  - Elements are returned in a particular order

A Java Implementation for Iterator

```
class BinTree<T> implements Iterable<T> {
    BinTree<T> left;
    BinTree<T> right;
    T val;
    ...
    // other methods: insert, delete, lookup, ...

    public Iterator<T> iterator() {
        return new TreeIterator(this);
    }
    private class TreeIterator implements Iterator<T> {
        private Stack<BinTree<T>> s = new Stack<BinTree<T>>();
        TreeIterator(BinTree<T> n) {
            if (n.val != null) s.push(n);
        }
        public boolean hasNext() {
            return !s.empty();
        }
        public T next() {
            if (!hasNext()) throw new NoSuchElementException();
            BinTree<T> n = s.pop();
            if (n.right != null) s.push(n.right);
            if (n.left != null) s.push(n.left);
            return n.val;
        }
        public void remove() {
            throw new UnsupportedOperationException();
        }
    }
}
```

Guarded Commands

- New and quite different forms of selection and loop structures were suggested by Dijkstra (1975)
- We cover guarded commands because they are the basis for two linguistic mechanisms developed later for concurrent programming in two languages: CSP and Ada

Motivations of Guarded Commands

- To support a program design methodology that ensures correctness during development rather than relying on verification or testing of completed programs afterwards
- Also useful for concurrency
- Increased clarity in reasoning

Guarded Commands

- Two guarded forms
  - Selection (guarded if)
  - Iteration (guarded do)

Guarded Selection

```
if <boolean> -> <statement>
[] <boolean> -> <statement>
    ...
[] <boolean> -> <statement>
fi
```

- Sementics
  - When this construct is reached
    - Evaluate all boolean expressions
    - If more than one is true, choose one nondeterministically
    - If none is true, it is a runtime error
- Idea: **Forces** one to consider **all possibilities**

An Example

```
if i = 0 -> sum := sum + i
[] i > j -> sum := sum + j
[] j > i -> sum := sum + i
fi
```

- If i = 0 and j > i, the construct chooses nondeterministically between the first and the third assignment statements
- If i == j and i ≠ 0, none of the conditions is true and a runtime error occurs

Guarded Selection

- The construction can be an elegant way to state that the order of execution, in some cases, is irrelevant

```
if x >= y -> max := x
[] y >= x -> max := y
fi
```

  - E.g., if x == y, it does not matter which we assign to max
  - This is a form of abstraction provided by the nondeterministic semantics

Guarded Iteration

```
do <boolean> -> <statement>
[]  <boolean> -> <statement>
      ...
[]  <boolean> -> <statement>
od
```

- Semantics:
  - – For each iteration
    - Evaluate all boolean expressions
    - If more than one is true, choose one nondeterministically, and then start loop again
    - If none is true, exit the loop
- Idea: if the order of evaluation is not important, the program should not specify one

An Example

```
do q1 > q2 -> temp := q1; q1 := q2; q2 := temp;
[] q2 > q3 -> temp := q2; q2 := q3; q3 := temp;
[] q3 > q4 -> temp := q3; q3 := q4; q4 := temp;
od
```

- Given four integer variables: q1, q2, q3, and q4, rearrange the values so that $q1 \le q2 \le q3 \le q4$
- Without guarded iteration, one solution is to put the values into an array, sort the array, and then assigns the value back to the four variables

An Example

- While the solution with guarded iteration is not difficult, it requires a good deal of code
- There is considerably increased complexity in the implementation of the guarded commands over their conventional deterministic counterparts

Reference

[1] Robert W. Sebesta, Concepts of Programming Languages, 8th edition, pg. 311-338

Semantic Analysis

In Text: Chapter 4

Outline [1]

- Static semantics
  - Attribute grammars
- Dynamic semantics
  - Operational semantics
  - Denotational semantics

Syntax vs. Semantics

- Syntax concerns the form of a valid program
- Semantics concerns its **meaning**
- Meaning of a program is important
  - It allows us to enforce rules, such as type consistency, which go beyond the form
  - It provides the information needed to generate an equivalent output program

Two types of semantic rules

- Static semantics
- Dynamic semantics

Static Semantics

- There are some characteristics of the structure of programming languages that are difficult or impossible to describe with BNF
  - E.g., type compatibility: a floating-point value cannot be assigned to an integer type variable, but the opposite is legal

Static Semantics

- The static semantics of a language is only indirectly related to the meaning of programs during execution; rather, it has to do with the legal forms of programs
  - Syntax rather than semantics
- Many static semantic rules of a language state its type constraints

Dynamic semantics

- It describes the meaning of expressions, statements, and program units
- Programmers need dynamic semantics to know precisely what statements of a language do
- Compiler writers need define the semantics of the languages for which they are writing compilers

Role of Semantic Analysis

- Following parsing, the next two phases of the "typical" compiler are
  - **semantic analysis**
  - (intermediate) code generation

Role of Semantic Analysis

- The principal job of the semantic analyzer is to enforce static semantics
  - Constructs a syntax tree (usually first)
  - Performs analysis of information that is gathered
  - Uses that information later during code generation

Conventional Semantic Analysis

- Compile-time analysis and run-time "actions" that enforce language-defined semantics
  - Static semantic rules are enforced at compile time by the compiler
    - Type checking
  - Dynamic semantic rules are enforced at runtime by the compiler-generated code
    - Bounds checking

STATIC SEMANTICS

Attribute Grammar

- A device used to describe more of the structure of a programming language than can be described with a context-free grammar
- It provides a formal framework for decorating parse trees
- An attribute grammar is an extension to a context-free grammar

Attribute Grammar

- The extension includes
  - Attributes
  - Attribute computation functions
  - Predicate functions

A Running Example

- Context-Free Grammar (CFG)

```
<assign> -> <var> = <expr>
<expr>   -> <var> + <var>
<expr>   -> <var>
<var>    -> A | B | C
```

- Note:
  - It only focuses on potential structured sequence of tokens
  - It says nothing about the meaning of any particular program

Attributes

- Associated with each grammar symbol X is a set of attributes A(X). The set A(X) consists of two disjoint sets: S(X) and I(X)

Attributes

- S(X): synthesized attributes, which are used to pass semantic information up a parse tree

Attributes

- I(X): inherited attributes, which pass semantic information down or across a tree. Similar to variables because they can also have values assigned to them

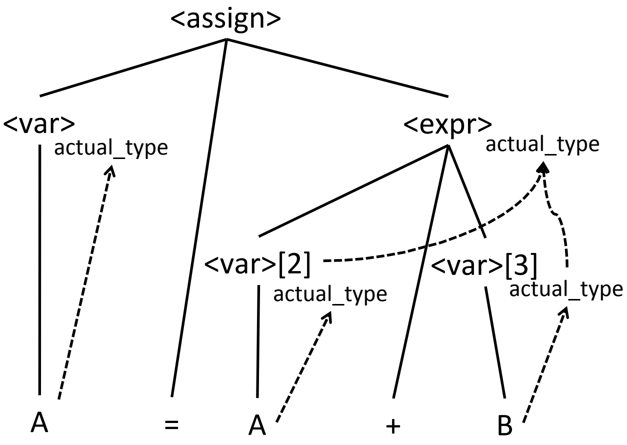
Intrinsic Attributes

- Synthesized attributes of leaf nodes whose values are determined outside the parse tree
  - E.g., the type of a variable can come from the symbol table
  - Given the intrinsic attribute values on a parse tree, the semantic functions can be used to compute the remaining attribute values

Example Synthesized Attribute

- *actual_type*
  - A synthesized attribute associated with nonterminals: <var> and <expr>
  - It is used to store the actual type, int or real, of a variable or expression
  - For each variable, the actual_type is intrinsic
  - For expressions and assignments, the attribute is determined by the actual types of children nodes

Evaluation Order of Synthesized Attribute *actual_type*



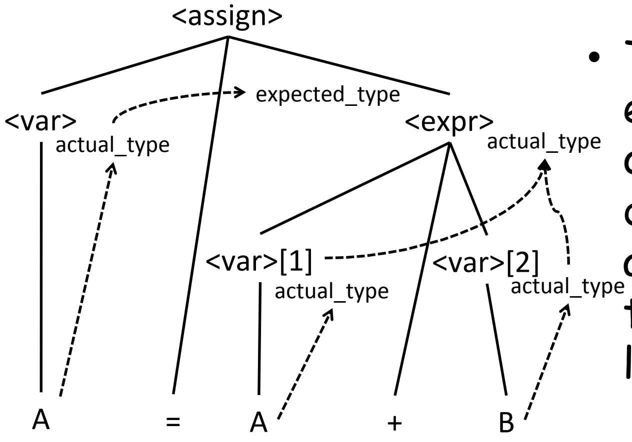
- Parser tree of A = A + B
- A and B have type “real” or “int” according to the symbol table

Example Inherited Attribute

- *expected_type*
    - An inherited attribute associated with the nonterminal <expr>
    - It is used to store the expected type, either int or real
    - It is determined by the type of the variable on the left side of the assignment statement

---

Evaluation Order of Inherited Attribute *expected_type*



- The expected_type of <expr> is decided by the actual_type of the assignment's left side

Attribute Grammar

- Defines the attributes, and attribute evaluation rules mentioned in the example

Example Attribute Grammar

Syntax Rule	Semantic Rule
<assign> -> <var> = <expr>	R1. <expr>.expected_type <- <var>.actual_type
<expr> -> <var>[1] + var[2]	R2. <expr>.actual_type <- if (<var>[2].actual_type = int) and (<var>[3].actual_type = int) then int else real end if predicate: <expr>.actual_type == <expr>.expected_type
<expr> -> <var>	R3. <expr>.actual_type <- <var>.actual_type predicate: <expr>.actual_type == <expr>.expected_type
<var> -> A | B | C	R4. <var>.actual_type <- look-up(<var>.string) The look-up function looks up a given variable name in the symbol table and returns the variable's type

Semantic Functions

- Associated with each grammar rule is a set of semantic functions and a possibly empty set of predicate functions over the attributes of the symbols in the grammar rule
- Specify how attribute values are computed for S(X) and I(X)

Semantic Functions

- For a rule X_0->X_1…X_n, the synthesized attributes of X_0 are computed with semantic functions of the form $S(X_0) = f(A(X_1), \ldots, A(X_n))$
- The value of a synthesized attribute on a parse tree node depends only on the attribute values of the children node

Semantic Functions

- Inherited attributes of symbols X_j, $1 \le j \le n$, are computed with a semantic function of the form $I(X_j) = f(A(X_0), …, A(X_n))$
- The value of an inherited attribute on a parse tree node depends on the attribute values of the node's parent and siblings
- To avoid circularity, inherited attributes are often restricted to functions of the form $I(X_j) = f(A(X_0), …, A(X_{j-1}))$

Revisit the Semantic Functions

Syntax Rule	Semantic Rule
<assign> -> <var> = <expr>	1. **<expr>.expected_type <- <var>.actual_type**
<expr> -> <var>[1] + var[2]	2. **<expr>.actual_type <- if (<var>[2].actual_type = int) and** **(<var>[3].actual_type = int)** **then int** **else real** **end if**
<expr> -> <var>	3. **<expr>.actual_type <- <var>.actual_type**
<var> -> A | B | C	4. **<var>.actual_type <- look-up(<var>.string)** **The look-up function looks up a given variable name in the symbol table and returns the variable's type**

Predicate Function

- A predicate function has the form of a Boolean expression on the union of the attribute set {$A(X_0)$, …, $A(X_n)$}, and a set of literal attribute values
- The only derivations allowed with an attribute grammar are those in which every predicate associated with every nonterminal is true
- A false predicate function value indicates a violation of the syntax or static semantic rules

Example Semantic Rules & Predicates

Syntax Rule	Semantic Rule
<assign> -> <var> = <expr>	R1. <expr>.expected_type <- <var>.actual_type
<expr> -> <var>[1] + var[2]	R2. <expr>.actual_type <- if (<var>[1].actual_type = int) and (<var>[2].actual_type = int) then int else real end if **predicate: <expr>.actual_type == <expr>.expected_type**
<expr> -> <var>	R3. <expr>.actual_type <- <var>.actual_type **predicate: <expr>.actual_type == <expr>.expected_type**
<var> -> A | B | C	R4. <var>.actual_type <- look-up(<var>.string) The look-up function looks up a given variable name in the symbol table and returns the variable's type