5. Semantic Analysis

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http://www.cs.ucla.edu/~palsberg/
http://www.cs.purdue.edu/homes/hosking/
William Tell is a folk hero of Switzerland; she was an exceptional marksman.
Conference in Vienna in 1964 best summarized by T. B. Steel:

"I don’t fully know myself how to describe the semantics of a language. I daresay nobody does or we wouldn’t be here"

*The Genesis of Attribute Grammars*
Donald E. Knuth
Roadmap

> Context-sensitive analysis
> Strategies for semantic analysis
> Attribute grammars
> Symbol tables and type-checking

Roadmap

> Context-sensitive analysis
> Strategies for semantic analysis
> Attribute grammars
> Symbol tables and type-checking
On error, compilation should stop and no code must be generated.
Compilation is **driven by the syntactic structure of the program as discovered by the parser**

Semantic routines:
- interpret meaning of the program based on its syntactic structure
- two purposes:
  - **finish analysis** by deriving context-sensitive information
  - **begin synthesis** by generating the IR or target code
- associated with individual productions of a context free grammar or sub-trees of a syntax tree

One of the main goals is to find errors early. If the instructions are ambiguous, or wrong, you don’t want to follow them.
Context-sensitive analysis

What context-sensitive questions might the compiler ask?

1. Is $x$ scalar, an array, or a function?
2. Is $x$ declared before it is used?
3. Are any names declared but not used?
4. Which declaration of $x$ is being referenced?
5. Is an expression type-consistent?
6. Does the dimension of a reference match the declaration?
7. Where can $x$ be stored? (heap, stack, ...)
8. Does $p$ reference the result of a malloc()?
9. Is $x$ defined before it is used?
10. Is an array reference in bounds?
11. Does function $foo$ produce a constant value?
12. Can $p$ be implemented as a memo-function?

*These questions cannot be answered with a context-free grammar*
What are the challenges?
- questions and answers involve non-local information
- answers depend on values, not syntax
- answers may involve computation

Several approaches:
- **symbol tables**: central store for facts; express checking code
- **attribute grammars**: specify non-local computations; automatic evaluators
- **language design**: simplify language; avoid problems
Roadmap

> Context-sensitive analysis
> **Strategies for semantic analysis**
> Attribute grammars
> Symbol tables and type-checking
Alternatives for semantic processing

- One-pass compiler and synthesis
- Two-pass
  - compiler + peephole
  - compiler & IR synthesis + code generation pass
- Multi-pass
  - analysis
  - synthesis
One-pass compilers

> Interleave scanning, parsing and translation
  — no explicit IR
  — generate target code directly
    - emit short sequences of instructions on each parser action
    - little or no optimization possible (minimal context)

> Can add peephole optimization pass
  — extra pass over generated code through small window (“peephole”) of instructions
  — smooths out “rough edges” between code emitted by subsequent calls to code generator
## Two-pass: analysis & IR synthesis + code generation

> Generate explicit IR as interface to code generator
  > —linear (e.g., tuples)
  > —can emit multiple tuples at a time for better code context

> Advantages
  > —easier retargeting (IR must be expressive enough for different machines!)
  > —can add optimization pass later (multi-pass synthesis)

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Keyword here is explicit IR.  
IR can be: structural (AST) or linear (pseudo-code for abstract machine).
Multi-pass analysis

> Several passes, read/write intermediate files
  1. scan source file, generate tokens
     - place identifiers and constants in symbol table
  2. parse token file
     - generate semantic actions or linearized parse tree
  3. process declarations to symbol table
  4. semantic checking with IR synthesis

> Motivations:
  — Historical: constrained address spaces
  — Language: e.g., declaration after use
  — Multiple analyses over IR tree
Multi-pass synthesis

> Passes operate on linear or tree-structured IR
> Options:
  — code generation and peephole optimization
  — multi-pass IR transformation
    - machine-independent then dependent optimizations
  — high-level to low-level IR transformation before code generation
    - e.g., in gcc high-level trees drive generation of low-level Register Transfer Language for machine-independent optimization
  — language-independent front ends
  — retargetable back ends
Roadmap

- Context-sensitive analysis
- Strategies for semantic analysis
- Attribute grammars
- Symbol tables and type-checking
Attribute grammars

> Add attributes to the syntax tree or PEG:
  — can add attributes (fields) to each node
  — specify equations to define values
  — propagate values up (synthesis) or down (inheritance)

> **Example:** ensuring that constants are immutable
  — add *type* and *class* attributes to expression nodes
  — add rules to production for `:=`
    1. *check that LHS.class is variable (not constant)*
    2. *check that LHS.type and RHS.type are compatible*

**Synthesized Attributes**
- derives values from constants and children
- when only Synthesized => S-attributed grammar

**Inherited Attributes**
- derived from constants, siblings, and parents
- used for context checking
Attribute grammar actions

<table>
<thead>
<tr>
<th>PRODUCTION</th>
<th>SEMANTIC RULES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \rightarrow T \ L$</td>
<td>$L.in := T.type$</td>
</tr>
<tr>
<td>$T \rightarrow \text{int}$</td>
<td>$T.type := \text{integer}$</td>
</tr>
<tr>
<td>$T \rightarrow \text{real}$</td>
<td>$T.type := \text{real}$</td>
</tr>
<tr>
<td>$L \rightarrow L_1 \ , \ id$</td>
<td>$L_{1}\ .in := L.in$</td>
</tr>
<tr>
<td>$L \rightarrow id$</td>
<td>$\text{addtype}(id.entry, L.in)$</td>
</tr>
</tbody>
</table>

- tree attributes specified by grammar
- productions associated with attribute assignments
- each attribute defined uniquely and locally
- identical terms are labeled uniquely
Example: evaluating signed binary numbers

- val and neg are **synthetic** attributes
- pos is an **inherited** attribute

Note that the val attributes propagate upwards while the pos attributes propagate downward. The production rule List -> List1 Bit must be left recursive; otherwise the algorithm won’t work.
Attribute dependency graph

- **nodes** represent **attributes**
- **edges** represent **flow of values**
- **graph** must be **acyclic**
- **topologically sort** to order attributes
  - use this order to evaluate rules
  - order depends on both grammar and input string!

```
1. SIGN.neg  8. BIT0.val
2. LIST0.pos 9. LIST2.val
3. LIST1.pos 10. BIT1.val
4. LIST2.pos 11. LIST1.val
5. BIT0.pos 12. BIT2.val
6. BIT1.pos 13. LIST0.val
7. BIT2.pos 14. NUM.val
```

*Evaluating in this order yields NUM.val = -5*
Evaluation strategies

> **Parse-tree methods**
1. build the parse tree
2. build the dependency graph
3. topologically sort the graph
4. evaluate it

> **Rule-based methods**
1. analyse semantic rules at compiler-construction time
2. determine static ordering for each production’s attributes
3. evaluate its attributes in that order at compile time

> **Oblivious methods**
1. ignore the parse tree and the grammar
2. choose a convenient order (e.g., left-to-right traversal) and use it
3. repeat traversal until no more attribute values can be generated
### Attribute grammars in practice

#### Advantages
- Clean formalism
- Automatic generation of evaluator
- High-level specification

#### Disadvantages
- Evaluation strategy determines efficiency
- Increase space requirements
- Parse tree evaluators need dependency graph
- Results distributed over tree
- Circularity testing

Historically, attribute grammars have been judged too large and expensive for industrial-strength compilers.

Haskell’s lazy evaluation makes it an ideal platform for evaluating attribute grammars. See, for example, UUAGC, the *Utrecht University Attribute Grammar Compiler*.
Roadmap

> Context-sensitive analysis
> Strategies for semantic analysis
> Attribute grammars
> **Symbol tables and type-checking**
### Symbol tables

- For compile-time efficiency, compilers often use a **symbol table**:  
  — associates lexical *names* (symbols) with their *attributes*

- What items should be entered?  
  — variable names  
  — constants  
  — procedure and function names  
  — literal constants and strings  
  — compiler-generated temporaries (we'll get there)

- Separate table of structure layouts for types (field offsets and lengths)

> *A symbol table is a compile-time structure*
Symbol table information

What kind of information might the compiler need?

- textual name
- data type
- dimension information (*for aggregates*)
- declaring procedure
- **lexical level** of declaration
- storage class (*heap, stack, text …*)
- offset in storage
- if record, pointer to structure table
- if parameter, by-reference or by-value?
- can it be aliased? to what other names?
- number and type of arguments to functions
Some older languages provided dynamic scoping, but it is much harder to reason about. Nowadays only exception handlers are dynamically scoped.
Nested scopes: block-structured symbol tables

> What information is needed?
   — when we ask about a name, we want the most recent declaration
   — the declaration may be from the current scope or some enclosing scope
   — innermost scope overrides declarations from outer scopes

> Key point: new declarations (usually) occur only in current scope

> What operations do we need?
   — void put(Symbol key, Object value) — bind key to value
   — Object get(Symbol key) — return value bound to key
   — void beginScope() — remember current state of table
   — void endScope() — restore table to state at most recent scope that has not been ended

May need to preserve list of locals for the debugger
Checking variable declarations in a hierarchical symbol table

```c
int x=1;
{
    int y = x;
    x = x+y;
}
{
    y = x - y;
}
```
Efficient Implementation of Symbol Tables

Implementation options
1. functional
2. imperative

How to ensure efficiency, with thousands of distinct identifiers in a large program?

Efficient data structures
Symbols instead of strings: comparing & hashing are fast.
Hash tables support an imperative (destructive) implementation

If we have multiple symbols in the new environment we must have a stack to keep track of the symbols in each environment. With red we are trying to copy the array. That is not efficient!
(Balanced) binary trees support a functional (non-destructive) implementation. A persistence data structure.

Question: How fast is the copying of the needed nodes to create an entry point for a new environment? To insert a node at depth n I have to add a maximum of n nodes. Thus insertion, and search can all happen in log(n) time.
Attribute information

> Attributes are internal representations of declarations
> Symbol table associates names with attributes

> Names may have different attributes depending on their meaning:
  — *variables*: type, procedure level, frame offset
  — *types*: type descriptor, data size/alignment
  — *constants*: type, value
  — *procedures*: formals (names/types), result type, block information (local decls.), frame size
Static and Dynamic Typing

A language is **statically typed** if it is always possible to determine the (static) type of an expression based on the program text alone.

A language is **dynamically typed** if only values have fixed type. Variables and parameters may take on different types at run-time, and must be checked immediately before they are used.

A language is “strongly typed” if it is impossible to perform an operation on the wrong kind of object.

Type consistency may be assured by

1. compile-time type-checking,
2. type inference, or
3. dynamic type-checking.

See: Programming Languages course
Type expressions

Type expressions are a textual representation for types:
1. basic types: boolean, char, integer, real, etc.
2. type names
3. constructed types (constructors applied to type expressions):
   a) array(I,T) denotes array of elements type T, index type I
e.g., array (1...10,integer)
   b) $T_1 \times T_2$ denotes Cartesian product of type expressions $T_1$ and $T_2$
   c) record(…) denotes record with named fields
e.g., record((a × integer), (b × real))
   d) pointer(T) denotes the type “pointer to object of type T”
   e) $D \rightarrow R$ denotes type of function mapping domain D to range R
e.g., integer × integer → integer
Type descriptors are compile-time structures representing type expressions

e.g., char × char → pointer(integer)
Type compatibility

Type checking needs to determine type equivalence.

Two approaches:

> **Name equivalence**: each type name is a distinct type

> **Structural equivalence**: two types are equivalent iff they have the same structure (after substituting type expressions for type names)

- \( s = t \) iff \( s \) and \( t \) are the same basic types
- \( \text{array}(s_1, s_2) = \text{array}(t_1, t_2) \) iff \( s_1 = t_1 \) and \( s_2 = t_2 \)
- \( s_1 \times s_2 = t_1 \times t_2 \) iff \( s_1 = t_1 \) and \( s_2 = t_2 \)
- \( \text{pointer}(s) = \text{pointer}(t) \) iff \( s = t \)
- \( s_1 \rightarrow s_2 = t_1 \rightarrow t_2 \) iff \( s_1 = t_1 \) and \( s_2 = t_2 \)

Java uses nominal (i.e., named), not structural types. Structural typing could lead to accidental equivalence of types that should be considered different (e.g., polar and Cartesian points).
Type compatibility: example

Consider:

```plaintext
type link = ^cell
var next : link;
var last : link;
var p : ^cell;
var q, r : ^cell;
```

Under name equivalence:

— `next` and `last` have the same type
— `p`, `q` and `r` have the same type
— `p` and `next` have different type

Under structural equivalence all variables have the same type

Ada/Pascal/Modula-2 are somewhat confusing: they treat distinct type definitions as distinct types, so

— `p` has different type from `q` and `r` (!)
Type compatibility: Pascal-style name equivalence

Build compile-time structure called a **type graph**:
- each constructor or basic type creates a node
- each name creates a leaf (associated with the type’s descriptor)

*Type expressions are equivalent if they are represented by the same node in the graph*
Type compatibility: recursive types

Consider:

```pascal
type link = ^cell
var cell = record
  info : integer;
  next : link;
end
```

Expanding `link` in the type graph yields:
Type compatibility: recursive types

Allowing cycles in the type graph eliminates `cell`:
Type rules

Type-checking rules can be formalized to prove soundness and correctness.

\[
\frac{f : A \rightarrow B, x : A}{f(x) : B}
\]

If \( f \) is a function from \( A \) to \( B \), and \( x \) is of type \( A \), then \( f(x) \) is a value of type \( B \).
Example: Featherweight Java

Used to prove that generics could be added to Java without breaking the type system.

Igarashi, Pierce and Wadler, “Featherweight Java: a minimal core calculus for Java and GJ”, OOPSLA ’99 
doi.acm.org/10.1145/320384.320395
Can you answer these questions?

- Why can semantic analysis be performed by the parser?
- What are the pros and cons of introducing an IR?
- Why must an attribute dependency graph be acyclic?
- Why would be the use of a symbol table at run-time?
- Why does Java adopt nominal (name-based) rather than structural type rules?
What you should know!

- Why is semantic analysis mostly context-sensitive?
- What is “peephole optimization”?
- Why was multi-pass semantic analysis introduced?
- What is an attribute grammar? How can it be used to support semantic analysis?
- What kind of information is stored in a symbol table?
- How is type-checking performed?
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