Lecture 12: AST visitors, ad-hoc semantic analysis

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October 9, 2024

601.428/628 Compilers and Interpreters

Agenda

- Semantic analysis
- AST visitors
- Ad-hoc semantic analysis, symbol tables
- An example

Semantic analysis

- Parser establishes whether or not the input source is *syntactically* value
- This does not guarantee that the input is *semantically* valid
  - E.g., `int x = "hello";`
- Semantic analysis:
  - Check that names refer to something valid
  - Check that operations performed are consistent with the source language's semantics

Formal vs. ad-hoc techniques

- With lexical analysis and parsing, formal techniques are very effective
  - Lexical analysis: regular languages, regular expressions, finite automata
  - Parsing: context-free grammars, parsing algorithms
- Formal approach to semantic analysis: *attribute grammars*
  - Never widely used, we will (probably) not cover them
- *Ad-hoc semantic analysis*: write ad-hoc code to check semantic properties
  - Could execute during parsing
  - Could execute on a representation of the input source (i.e., the AST)

AST visitors

Doing a computation on a tree

```
// approach 1
void TreeComputation::process_tree(Node *n) {
  switch (n->get_tag()) {
  case NODE_TAG_1:
    ...code to handle NODE_TAG_1...
    ...recursively process children...
    break;
  case NODE_TAG_2:
    ...code to handle NODE_TAG_2...
    ...recursively process children...
    break;
  ...etc...
  }
}
```

Doing a computation on a tree

```
// approach 2
void TreeComputation::process_tree(Node *n) {
  switch (n->get_tag()) {
  case NODE_TAG_1:
    visit_node_tag_1(n); // will also process children
    break;
  case NODE_TAG_2:
    visit_node_tag_2(n); // will also process children
    break;
  ...etc...
  }
}
```

Observation

- Lots of repetitive code
- Second approach is nice in that each kind of tree node is handled by a dedicated function
  - But the big switch statement is still tedious and error-prone code
- Also: what if we have multiple tree computations?
  - Potential for duplicated code

Visitor design pattern

- Idea: abstract the traversal and dispatching to per-node-type functions into a base class
- Derived classes then only need to override the per-node-type member functions as necessary

ASTVisitor

- `ASTVisitor`: a base class for implementations of tree computations on the AST
  - Assignment 3: `SemanticAnalysis`
  - Assignment 4: high-level code generation

ASTVisitor

```
class ASTVisitor {
public:
  ASTVisitor();
  virtual ~ASTVisitor();

  virtual void visit(Node *n); // <-- switch statement is here
  virtual void visit_unit(Node *n);
  virtual void visit_variable_declaration(Node *n);
  ...many others...

  virtual void visit_children(Node *n); // <-- recursively visit children
  virtual void visit_token(Node *n);
};
```

General recursive treewalk

- The default behavior of each node-specific visit function is to call `visit_children`
- This means that the default behavior of any class derived from `ASTVisitor` is a general recursive treewalk of the AST
- Which is why a derived visitor class can just override the visit functions that it actually cares about

Defining a visit function

Note that if you override a node-specific visit function, then it's up to you to decide whether and how to visit children.

Example:

```
void SemanticAnalysis::visit_variable_declaration(Node *n) {
  // visit the base type
  visit(n->get_kid(1));
  std::shared_ptr<Type> base_type = n->get_kid(1)->get_type();

  // iterate through declarators, adding variables
  // to the symbol table
  Node *decl_list = n->get_kid(2);
  for (auto i = decl_list->cbegin(); i != decl_list->cend(); ++i) {
    Node *declarator = *i;
    // ...handle the declarator...
  }
}
```

Where results go

- The most straightforward way to record results is to store them *in the visited tree node*
- For example:
  - Store a pointer to a symbol table entry in a node representing a reference to a variable or function
  - Store a (shared) pointer to the `Type` object representing the type of an expression
  - Store a boolean value indicating whether or not an expression yields an lvalue

NodeBase

The purpose of the `NodeBase` class is to give you a place to define new member variables and member functions for AST nodes.

The reason we don't recommend that you modify `Node` directly is that we might want to give you a new version. Putting your changes in `NodeBase` means you never need to modify `Node`.

Propagation of values

- Propagating values *upwards* in the tree is generally easy, because the parent has links to its children
  - Recursively visit children, then make use of computed values stored in them
- Propagating values *downwards* is more difficult because child nodes don't link back to the parent
- Fortunately, upwards tends to be the most natural direction
- For the rare cases of propagating values downwards (e.g., for communicating the base type to the code that processes declarators) you might need to write some custom traversal code

Ad-hoc semantic analysis, symbol tables

Semantic analysis, symbol tables

Two of the main concerns of semantic analysis:

1. Determine what each name refers to
2. Determine a type for each expression

Building *symbol tables* is the classic approach to performing semantic analysis

SymbolTable = Environment

- If you're comfortable with the notion of "environment" from the interpreter project, a symbol table is more or less the same thing
  - Represents a scope in the program
  - Stores information about what names in that scope refer to
  - Can have a "parent" representing the enclosing scope
- The main difference is that `Environment` kept track of a runtime value for each name, while `SymbolTable` will keep track of information about a variable, function, or data type

Symbol class

```
// represents one symbol table entry
class Symbol {
private:
  SymbolKind m_kind;
  std::string m_name;
  std::shared_ptr<Type> m_type;
  SymbolTable *m_symtab;
  bool m_is_defined;

public:
  // constructor, member functions...
};
```

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Global scope →

Name	Kind	Type

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Global scope

Name	Kind	Type
struct Point	Type	struct { }

Name	Kind	Type

Create entry and symbol table for the struct Point data type

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Global scope

Name	Kind	Type
struct Point	Type	struct Point { }

Name	Kind	Type
x	Var	int
y	Var	int

Entries for members of struct Point are added to its symbol table

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Global scope

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}

Name	Kind	Type
x	Var	int
y	Var	int

Full representation of struct Point is now known

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Global scope

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
move_horiz	Func	(ptr to struct Point × int) → void

Name	Kind	Type
x	Var	int
y	Var	int

Name	Kind	Type
p	Var	ptr to struct Point {x:int,y:int}
dx	Var	int

Add entry for move_horiz function, create symbol table for its parameters and body

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Visit function body,
add symbol table entries
for local variable(s)

Global scope

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
move_horiz	Func	(ptr to struct Point × int) → void

Name	Kind	Type
x	Var	int
y	Var	int

Name	Kind	Type
p	Var	ptr to struct Point {x:int,y:int}
dx	Var	int
u	Var	int

Symbol tables example

```
struct Point {
  int x, y;
};

void move_horiz(struct Point *p,
                int dx) {
  int u;
  u = p->x + dx;
  p->x = u;
}
```

Global scope

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
move_horiz	Func	(ptr to struct Point × int) → void

Name	Kind	Type
x	Var	int
y	Var	int

Name	Kind	Type
p	Var	ptr to struct Point {x:int,y:int}
dx	Var	int
u	Var	int

Variable references can be annotated with pointers to symbol table entries

Type checking

Type checking: based on the types of variables and literals, check each operation in the program to make sure the operand types are consistent with the language's semantic rules

Because C requires a declaration or definition to precede each use (for variables, functions, and types), the symbol table should have information about referenced names at the point of their use

Type checking examples

```
struct Point {
  int x, y;
};

void foo(struct Point *p) {
  int n;
  n = 3;
  q->x = n;
}
```

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
foo	Func	(ptr to struct Point{x:int,y:int}) → void

Name	Kind	Type
p	Var	ptr to struct Point{x:int,y:int}
n	Var	int

'q' is not defined in any currently-visible scope

Type checking examples

```
struct Point {
  int x, y;
};

void foo(struct Point *p) {
  int n;
  n = 3;
  p->z = n;
}
```

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
foo	Func	(ptr to struct Point{x:int,y:int}) → void

Name	Kind	Type
p	Var	ptr to struct Point{x:int,y:int}
n	Var	int

'p' is a pointer to a struct type, but that struct type doesn't have a member named 'z'

Type checking examples

```
struct Point {
  int x, y;
};

void foo(struct Point *p) {
  int n;
  n = 3;
  p->x = &n;
}
```

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
foo	Func	(ptr to struct Point{x:int,y:int}) → void

Name	Kind	Type
p	Var	ptr to struct Point{x:int,y:int}
n	Var	int

Assignment of pointer to int variable: 'p->x' is an int lvalue, '&n' is a pointer to int rvalue

Type checking examples

```
struct Point {
  int x, y;
};

void foo(struct Point *p) {
  int n;
  n = 3;
  *p = n;
}
```

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
foo	Func	(ptr to struct Point{x:int,y:int}) → void

Name	Kind	Type
p	Var	ptr to struct Point{x:int,y:int}
n	Var	int

Assignment of int rvalue
to struct Point lvalue
(types are not compatible)

Type checking examples

```
struct Point {
  int x, y;
};

void foo(struct Point *p) {
  int n;
  n = 3;
  p->x = n[0];
}
```

Name	Kind	Type
struct Point	Type	struct Point {x:int,y:int}
foo	Func	(ptr to struct Point{x:int,y:int}) → void

Name	Kind	Type
p	Var	ptr to struct Point{x:int,y:int}
n	Var	int

'n' is neither a pointer
nor an array

Semantic analysis and type checking

To conclude:

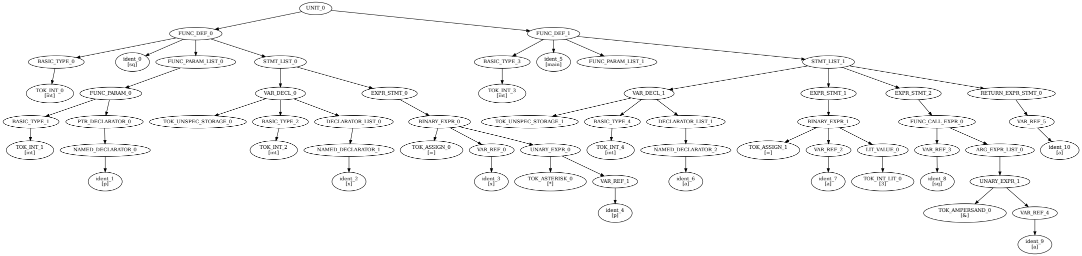
- The semantic analyzer builds symbol tables recording the name and type of each variable, function, and struct type
- The symbol tables can be used to check that each operation in the code follows the source language's semantic rules
- The symbol tables will also be useful (and necessary) for storage allocation and code generation

An example

An example

```
int sq(int *p) {
  int x;
  x = *p;
}

int main(void) {
  int a;
  a = 3;
  sq(&a);
  return a;
}
```


UNIT_0
FUNC_DEF_0
FUNC_DEF_1
BASIC_TYPE_0
ident_0
[sq]
FUNC_PARAM_LIST_0
STMT_LIST_0
BASIC_TYPE_3
ident_5
[main]
FUNC_PARAM_LIST_1
STMT_LIST_1
TOK_INT_0
[int]
FUNC_PARAM_0
VAR_DECL_0
EXPR_STMT_0
TOK_INT_3
[int]
VAR_DECL_1
EXPR_STMT_1
EXPR_STMT_2
RETURN_EXPR_STMT_0
BASIC_TYPE_1
PTR_DECLARATOR_0
TOK_UNSPEC_STORAGE_0
BASIC_TYPE_2
DECLARATOR_LIST_0
BINARY_EXPR_0
TOK_UNSPEC_STORAGE_1
BASIC_TYPE_4
DECLARATOR_LIST_1
BINARY_EXPR_1
FUNC_CALL_EXPR_0
VAR_REF_5
TOK_INT_1
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NAMED_DECLARATOR_0
TOK_INT_2
[int]
NAMED_DECLARATOR_1
TOK_ASSIGN_0
[=]
VAR_REF_0
UNARY_EXPR_0
TOK_INT_4
[int]
NAMED_DECLARATOR_2
TOK_ASSIGN_1
[=]
VAR_REF_2
LIT_VALUE_0
VAR_REF_3
ARG_EXPR_LIST_0
ident_10
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ident_1
[p]
ident_2
[x]
ident_3
[x]
TOK_ASTERISK_0
[*]
VAR_REF_1
ident_6
[a]
ident_7
[a]
TOK_INT_LIT_0
[3]
ident_8
[sq]
UNARY_EXPR_1
ident_4
[p]
TOK_AMPERSAND_0
[&]
VAR_REF_4
ident_9
[a]