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), could have "parent" call store value in child node, could add member variable(s) to visitor class, etc.

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

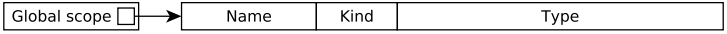
- If you're comfortable with the notion of "environment" from the interpreter project, a symbol table is more or less the same thing
  - Represents a scope in the program
  - Stores information about what names in that scope refer to
  - Can have a "parent" representing the enclosing scope
- The main 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...
};
```

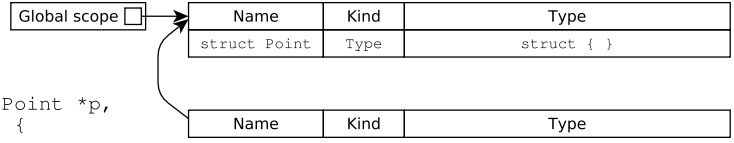
Symbol tables example

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

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



Symbol tables example

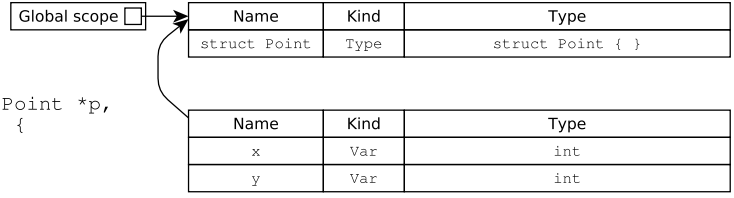
```
struct Point {
  int x, y;
};

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



Create entry and symbol table for the struct Point data type

Symbol tables example

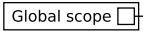
```
struct Point {
  int x, y;
};

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



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

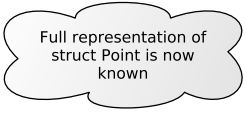
Symbol tables example

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

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



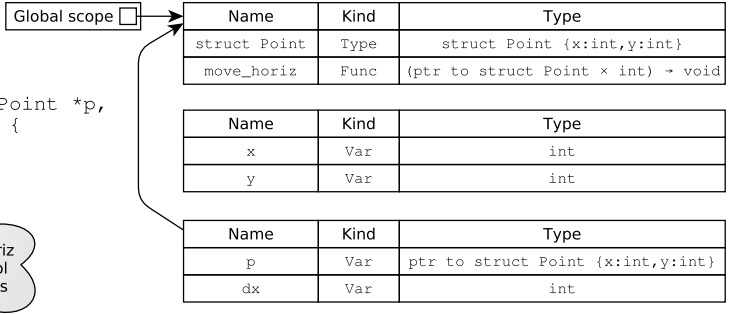
Name	Kind	Type
`struct Point`	`Type`	`struct Point{x:int,y:int}`

Name	Kind	Type
`x`	`Var`	`int`
`y`	`Var`	`int`



Symbol tables example

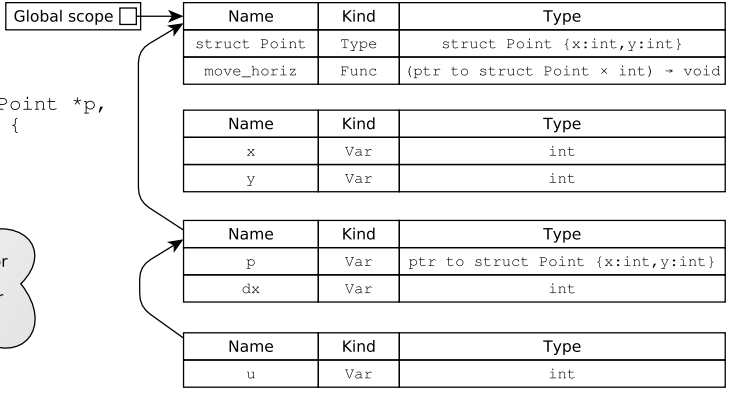
```
struct Point {
  int x, y;
};

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



Symbol tables example

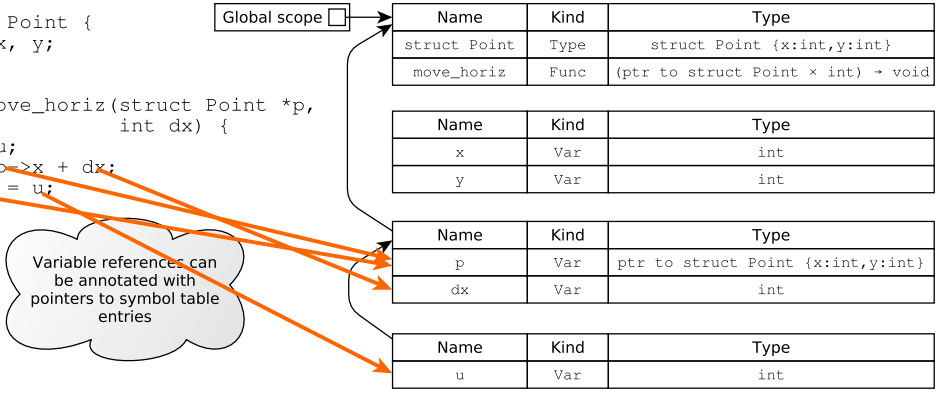
```
struct Point {
  int x, y;
};

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

Create symbol table for body of move_horiz function, add entry for local variable u



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;
}
```



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

Name	Kind	Type
u	Var	int

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;
}
```

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

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}

Name	Kind	Type
n	Var	int

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}

Name	Kind	Type
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}

Name	Kind	Type
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}

Name	Kind	Type
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}

Name	Kind	Type
n	Var	int

'n' is neither a pointer nor an array

Semantic analysis and type checking

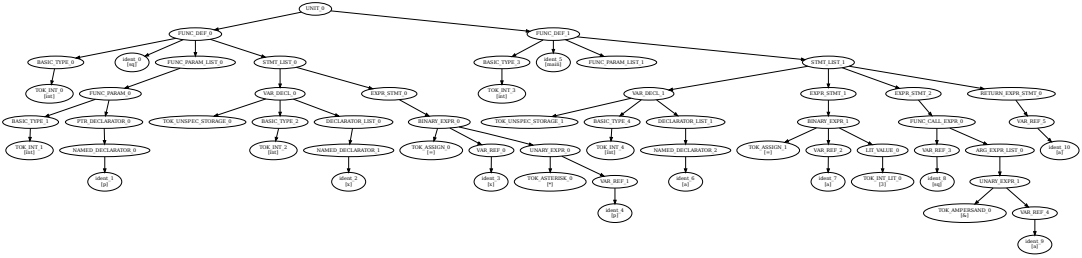
To conclude:

- 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_2
ident_1 [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_2
BASIC_TYPE_3
DECLARATOR_LIST_0
TOK_UNSPEC_STORAGE_3
BASIC_TYPE_4
DECLARATOR_LIST_1
BINARY_EXPR_1
FUNC_CALL_EXPR_0
VAR_REF_5
TOK_INT_1 [int]
NAMED_DECLARATOR_0
TOK_INT_2 [int]
NAMED_DECLARATOR_1
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 [n]
ident_3 [p]
TOK_ASSIGN_0 [=]
VAR_REF_0
UNARY_EXPR_0
VAR_REF_1
TOK_ASTERISK_2 [*]
ident_7 [n]
TOK_INT_LIT_0 [3]
ident_8 [sq]
UNARY_EXPR_2
ident_2 [n]
ident_4 [p]
ident_6 [n]
TOK_AMPERSAND_0 [&]
VAR_REF_4
ident_9 [a]