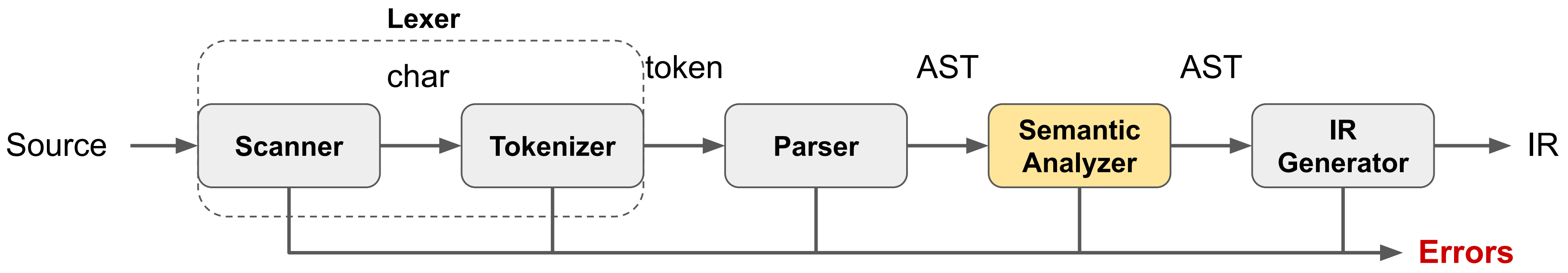
Compiling Techniques

Lecture 9: Semantic Analysis

From Syntax to Semantics



- The parser analyses the Syntax, ensuring that the raw text that forms the input program is syntactically well-formed

- In the Semantic Analysis we check if a syntactically well-formed program is also semantically well-formed.

We check if the program has a well-defined *meaning*.

Syntax vs. Semantic Error

ChocoPy programs with Syntax Errors

```
def foo():
4 + 3
^
```

```
def foo{}:
--------^
  4 + 3
```

```
def foo()
----------^
  4 + 3
```

```
def foo():
  4 plus 3
----^
```

```
def foo():
  4 + +
------^
```

If a program has a syntax error, we cannot build a valid AST for it!

ChocoPy programs with Semantic Errors

```
def foo():
  x + 3
```

x not declared

```
def foo():
  "4" + 3
```

Can't add `str` and `int`

```
def foo():
  4 = 3
```

Can't assign to a literal

```
def foo():
  foo(3)
```

`foo` expects no argument

```
def foo():
  x: int = 4
  x = "3"
```

Can't assign `str` to `int` variable

Programs with Semantic Errors have no meaning!

- We all have an intuition of what this program should *mean*:

```
def add(x: int, y: int) -> int:
    return x + y
```

- Our intuition can be mathematically formalized with an *operational semantics*
- Eventually we want to generate instructions corresponding to the operational semantics, here to perform an `add` instruction on two integer values.

- If our program has semantic errors, it has no operational semantics, and we do not know what instructions to generate.

These programs have no meaning!

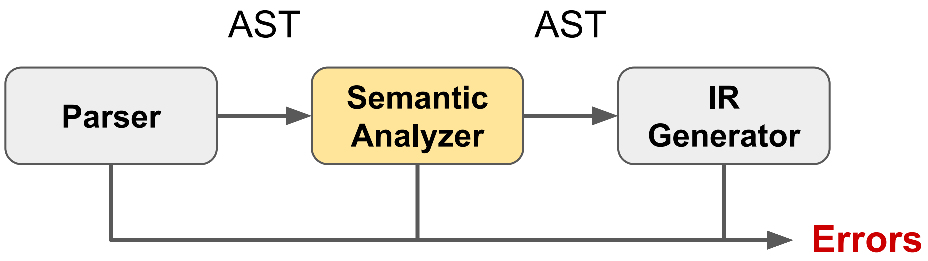
Q: How to detect Semantic Errors? A: Semantic Analysis

We are going to look at three different *Semantic Analysis* each checking for another kind of Semantic Error:

1. **Assign Target Analysis**
    - Check that the left-hand side of an assignment is a valid target.
2. **Name Analysis**
    - Check that all names (of variables and functions) are declared before they are used.
3. **Type Analysis**
    - Check that the program is well-typed given a set of typing rules.

Semantic Analysis as AST Tree Traversals

Each semantic analysis is implemented as a *pass* traversing the AST and checking for semantic errors

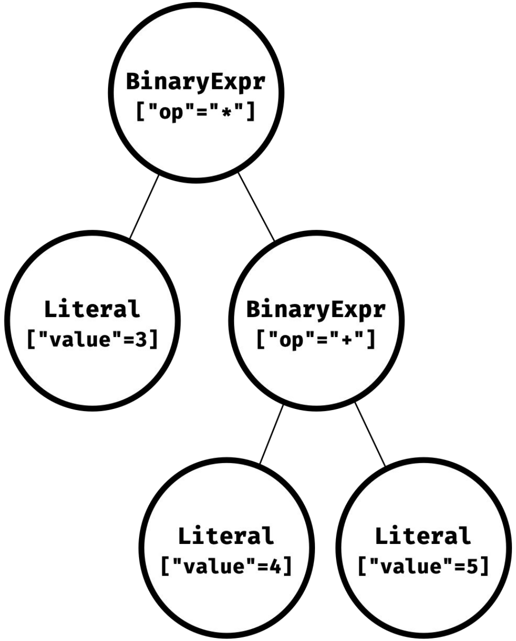


To help implement semantic analysis passes, we first implement a generic AST traversal

AST Traversal in xDSL

- Reminder: in xDSL all AST nodes are represented as Operations
- The nested tree structure is achieved by Regions

```
choco.ast.binary_expr() <{"op" = "*"}> ({
  choco.ast.literal() <{"value" = 3 : i32}>
}, {
  choco.ast.binary_expr() <{"op" = "+"}> ({
     choco.ast.literal() <{"value" = 4 : i32}>
  }, {
     choco.ast.literal() <{"value" = 5 : i32}>
  })
})
```



First simple AST Visitor

One class with two functions:

- `traverse` to iterate over the tree nodes
- `visit` is called once per AST node, should be overloaded by subclass

xDSL makes writing an AST visitor super easy!

```
class Visitor:

    def traverse(self, operation: Operation):
        for r in operation.regions:
            for op in r.ops:
                self.traverse(op)

        self.visit(operation)

    def visit(self, operation: Operation):
        pass
```

Simple Printer with AST Visitor

- Print name of each operation in the AST.
- `SimplePrinter` is a subclass of `Visitor` and overloads the `visit` method

```
class Visitor:
    def traverse(self, operation: Operation): ...
    def visit(self, operation: Operation): pass

class SimplePrinter(Visitor):
    def visit(self, operation: Operation):
        print(operation.name)   # print operation name

SimplePrinter().traverse( BinaryExpr.get( ... ) )
```

A better AST Visitor

What if we only want to visit AST nodes of a certain type?

Idea: have separate visit methods for each AST node type!

```
class Visitor:
  def traverse(self, operation: Operation):
    for r in operation.regions:
      …

    if isinstance(operation, BinaryExpr):
      self.visit_binary_expr(operation)
    elif isinstance(operation, Literal):
      self.visit_literal(operation)

  def visit_binary_expr(self, e: BinaryExpr): pass
  def visit_literal(self, l: Literal): pass
```

A generic better AST Visitor

Use Python dynamic reflection features to avoid boilerplate code:

```python
class Visitor:
  def traverse(self, op: Operation):
    # get class name of operation in snake_case
    op_class_name = camel_to_snake(type(op).__name__)
    for r in op.regions:
      ...
    # check if subclass has implemented a method with name visit_op_class_name
    # return method if it exists; otherwise None is returned
    visit = get_method(self, f"visit_{op_class_name}")
    if visit:
       visit(op)  # if the visit_op_class_name method exists call it
```

A flexible AST Visitor

What if we want to influence the traversal of certain AST nodes?

Idea: allow subclasses to implement `traverse_class_name` methods and prefer them over the generic traversal!

```
class Visitor:
  def traverse(self, op: Operation):
    class_name = camel_to_snake(type(op).__name__)
    traverse = get_method(self, f"traverse_{class_name}")
    if traverse:  # if a traverse_class_name method
                  # exists call it
      traverse(operation)
    else:         # otherwise do the generic traversal
      for r in op.regions:
        ...
    visit = get_method(self, f"visit_{class_name}")
    if visit:
      visit(op)
```

Assign Target Analysis

- The grammar from CW1 allows for arbitrary expressions on the left-hand side of an assignment, but this allows for example:

```
4 = x + 1
```

```
…
simple_stmt := `pass`
             | expr
             | `return` [expr]?
             | [expr `=`]+ expr
…
```

- **Assign Target Analysis**
  - Check that left-hand side of all assignments is either:
    - a variable name; or

      ```
      x = 4 + 5
      ```
    - an index into a list

      ```
      x[0] = 4 + 5
      ```

Assign Target Analysis Pass in xDSL

```python
def check_assign_target(_: MLContext, module: ModuleOp) -> ModuleOp:

    class AssignVisitor(Visitor):
        # visit every assign AST node
        def visit_assign(self, assign: Assign):
            # select the target operation
            target_op = assign.target.ops[0]
            # check if it is a variable name or an index expression
            if isinstance(target_op, ExprName):    return
            if isinstance(target_op, IndexExpr):   return
            # if not: raise a Semantic Error
            raise SemanticError(
                f'Found {type(target_op).__name__} as the left-hand side of an assignment. '
                f'Expected to find variable name or index expression only.')

    AssignVisitor().traverse(module)
    return module
```

Name Analysis

- Check names of variables and functions are declared before they are used
- We need to remember what names have been declared
  - For this we construct a context (aka, environment) that reflects the *scopes* in the program

```python
1 x: int = 4
2 def foo(x: int):
3     print(x)
4 def bar():
5     y: int = 0
6     y = x * x
7     print(y)
8
9 foo(5)
10 bar()
```

```python
CtxType = Dict[str, Optional['CtxType']]
ctx: CtxType = {
  "x": None,    # variable from line 1
  "foo": {      # function from line 2
    "x": None   # parameter from line 2
  },
  "bar": {      # function from line 4
    "y": None   # variable from line 5
  },
}
```

Scopes

Definition

The ***scope of an identifier*** is the part of the program where that identifier is valid.

- It is *only legal* to refer to an identifier within their scope.

- It is *illegal* to declare two identifiers with the same name and the same scope
- It is *legal* to declare a variable in a nested scope, this then *shadows* the identifier in the outer scope which can no longer be accessed.

- Variables that are not declared inside a function have *global scope*.

Name Analysis

- Can we construct the scoping context while we traverse the AST?

Name Analysis

- Can we construct the scoping context while we traverse the AST?
- **No!** Consider for example:

```
def foo():
    bar()
def bar():
    foo()
```

- To check `foo`, we need to know that `bar` is a valid name
- To check `bar`, we need to know that `foo` is a valid name

Name Analysis

- Can we construct the scoping context while we traverse the AST?
- **No!** Consider for example:

```
def foo():
    bar()
def bar():
    foo()
```

- To check `foo`, we need to know that `bar` is a valid name
- To check `bar`, we need to know that `foo` is a valid name

We implement Name Analysis by traversing the AST twice,
first to build the context and then a second time for checking.

Name Analysis: Part I - Construct the Name Context

```
class BuildContextVisitor(Visitor):
  name_ctx: NameCtx   # class to manage the name context
  # for every variable definition
  def visit_var_def(self, var_def: VarDef):  # add variable name to the current name context
    self.name_ctx.add_var(var_def.typed_var.ops[0].var_name.data)
```

Name Analysis: Part I - Construct the Name Context

```
class BuildContextVisitor(Visitor):
  name_ctx: NameCtx   # class to manage the name context
  # for every variable definition
  def visit_var_def(self, var_def: VarDef):  # add variable name to the current name context
    self.name_ctx.add_var(var_def.typed_var.ops[0].var_name.data)
  # for every function definition
  def traverse_func_def(self, func_def: FuncDef):
    # prepare a visitor for the function body …
    body_visitor = BuildContextVisitor(NameCtx(parent_scope=self.name_ctx))
    # … add the function parameters to the nested name scope …
    for op in func_def.params.ops:     body_visitor.name_ctx.add_var(op.var_name.data)
    # … visit the function body to construct the nested name scope.
    for op in func_def.func_body.ops:  body_visitor.traverse(op)
    # finally, add function and nested scope to the current name context
    self.name_ctx.add_func(func_def.func_name.data, body_visitor.name_ctx)
```

Name Analysis: Part II - Checking

1. Check that `variables` are declared before they are used

```
class NameAnalysisVisitor(Visitor):
  name_ctx: NameCtx

  def visit_expr_name(self, expr_name: ExprName):
    if expr_name.id.data in self.name_ctx:
      return
    else:
      raise SemanticError(
          f'[Name Analysis Error]: '
          f"Identifier `{expr_name.id.data}' found that was not previously defined.")
   …
```

Name Analysis: Part II - Checking

2. Check that `functions` are declared before they are called

```
class NameAnalysisVisitor(Visitor):
  name_ctx: NameCtx
  …
  def visit_call_expr(self, call_expr: CallExpr):
    if call_expr.func.data in self.name_ctx:
      return
    else:
      raise SemanticError(
        f'[Name Analysis Error]: '
        f"Identifier `{call_expr.func.data}' found that was not previously defined.")
   …
```

Name Analysis: Part II - Checking

3. Make sure that function bodies are checked with the right name context

```
class NameAnalysisVisitor(Visitor):
  name_ctx: NameCtx
  …
  def traverse_func_def(self, func_def: FuncDef):
    # select the nested name context from the current name context …
    nested_ctx = self.name_ctx.get_func_ctx(func_def.func_name.data)
    # … and use the nested name context when traversing the function body
    body_visitor = NameAnalysisVisitor(nested_ctx)
    for op in func_def.func_body.ops:
      body_visitor.traverse(op)
   …
```

Name Analysis: Part II - Checking

4. Check that the iteration variable in a `for` was previously defined

```
class NameAnalysisVisitor(Visitor):
  name_ctx: NameCtx
  …
  def visit_for(self, for_op: For):
    if for_op.iter_name.data not in self.name_ctx:
      raise SemanticError(
        f'[Name Analysis Error]: '
        f"Identifier `{for_op.iter_name.data}' found that was not previously defined.")
   …
```

Name Analysis: Part II - Checking

5. Check that variables in `global` declarations are declared with global scope

```
class NameAnalysisVisitor(Visitor):
  name_ctx: NameCtx
  …
  def visit_global_decl(self, global_decl: GlobalDecl):
    if global_decl.decl_name.data in self.name_ctx.global_scope():
      return
    else:
      raise SemanticError(
        f'[Name Analysis Error]: '
        f"Identifier `{global_decl.decl_name.data}' not declared in global scope.")
  …
```

Name Analysis putting the parts together

Name Analysis pass first constructs the context and then performs the checking.

```python
def name_analysis(_: MLContext, module: ModuleOp) -> ModuleOp:
    # add print, len, and input functions to the global scope
    name_ctx = NameCtx()
    name_ctx.add_func("print", NameCtx())
    name_ctx.add_func("len", NameCtx())
    name_ctx.add_func("input", NameCtx())
    # first construct name context
    BuildContextVisitor(name_ctx).traverse(module)
    # then perform checking
    NameAnalysisVisitor(name_ctx).traverse(module)
    return module
```