Semantic Analysis

Ronghui Gu

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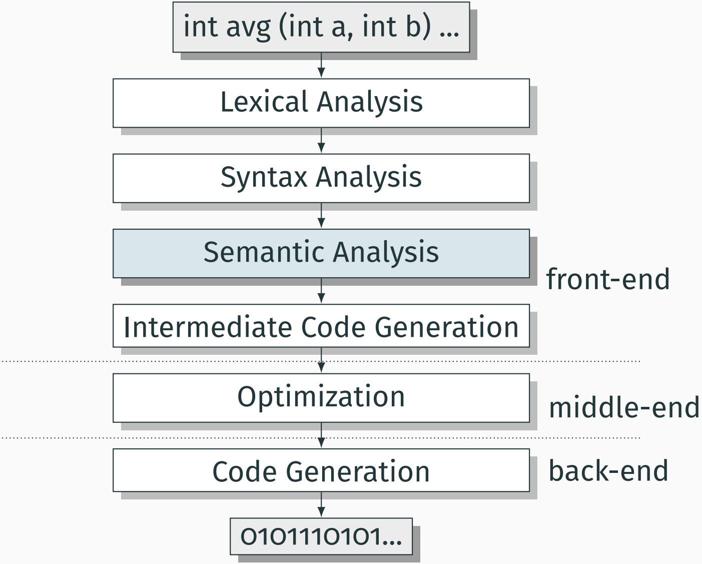
Columbia University

* Course website: https://verigu.github.io/4115Spring2024/

Semantic Analysis



Static Semantic Analysis

Lexical analysis: Each token is valid?

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for #a1123                    /* invalid tokens */
for break                     /* valid Java tokens */
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```

Syntactic analysis: Tokens appear in the correct order?

```
for break          /* invalid syntax */
return 3 + "f";    /* valid Java syntax */
```

Semantic analysis: Names used correctly? Types consistent?

```
return 3 + "f";      /* invalid */
return 3 + 13;       /* valid in Java */
```

What's Wrong With This?

$$\mathrm{a + f(b,\ c)}$$

What's Wrong With This?

$$a + f(b, c)$$

Scope questions:

Is a defined?

Is f defined?

Are b and c defined?

What's Wrong With This?

$$a + f(b, c)$$

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Is f defined?

Are b and c defined?

Type questions:

Is f a function of two arguments?

Can you add whatever a is to whatever f returns?

Does f accept whatever b and c are?

What To Check

Examples from Java:

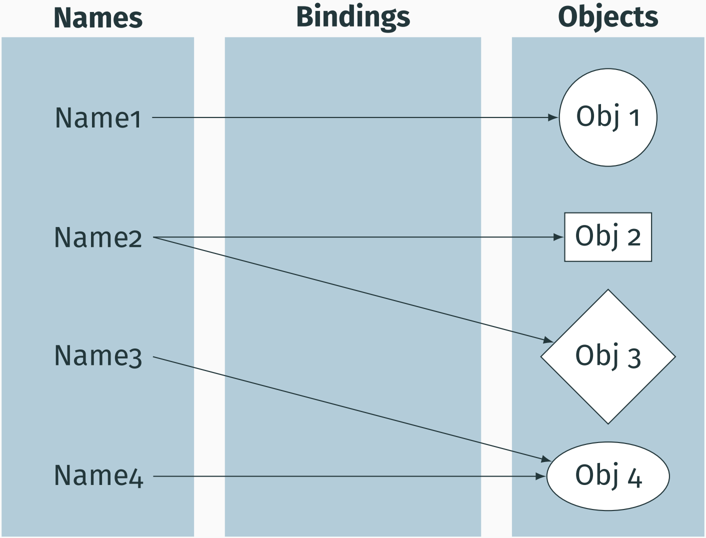
Verify names are defined (scope) and are of the right type (type).

```
int i = 5;
int a = z;    /* Error: cannot find symbol */
int b = i[3]; /* Error: array required, but int found */
```

Verify the type of each expression is consistent (type).

```
int j = i + 53;
int k = 3 + "hello";   /* Error: incompatible types */
int l = k(42);         /* Error: k is not a method */
if ("Hello") return 5; /* Error: incompatible types */
String s = "Hello";
int m = s;             /* Error: incompatible types */
```

Scope - What names are visible?


Names
Bindings
Objects
Name1
Name2
Name3
Name4
Obj 1
Obj 2
Obj 3
Obj 4

Scope

Scope: where/when a name is bound to an object

Useful for modularity: want to keep most things hidden

Scoping Policy	Visible Names Depend On
Static	Textual structure of program Names resolved by compile-time symbol tables Faster, more common, harder to break programs
Dynamic	Run-time behavior of program Names resolved by run-time symbol tables, e.g., walk the stack looking for names Slower, more dynamic

Basic Static Scope in C, C++, Java, etc.

A name begins life where it is declared and ends at the end of its block.

“The scope of an identifier declared at the head of a block begins at the end of its declarator, and persists to the end of the block.”

```
void foo()
{
  int x;
}
```

Hiding a Definition

Nested scopes can hide earlier definitions, giving a hole.

“If an identifier is explicitly declared at the head of a block, including the block constituting a function, any declaration of the identifier outside the block is suspended until the end of the block.”

```
void foo()
{
  int x;

  while ( a < 10 ) {
    int x;

  }


}
```

Basic Static Scope in O'Caml

A name is bound after the "in" clause of a "let." If the name is re-bound, the binding takes effect *after* the "in."

```
let x = 8 in


let x = x + 1 in
```

Returns the pair (12, 8):

```
let x = 8 in
 (let x = x + 2 in
   x + 2),
   x
```

Let Rec in O'Caml

The "rec" keyword makes a name visible to its definition. This only makes sense for functions.

```
let rec fib i =
  if i < 1 then 1 else
    fib (i-1) + fib (i-2)
in
  fib 5
```

```
(* Nonsensical *)
let rec x = x + 3 in
```

Static vs. Dynamic Scope

C

```c
int a = 0;

int foo() {
  return a;
}

int bar() {
  int a = 10;

  return foo();
}
```

OCaml

```ocaml
let a = 0 in
let foo x = a in
let bar =
  let a = 10 in
  foo 0
```

Bash

```bash
a=0

foo ()
{
  echo $a
}

bar ()
{
  local a=10
  foo
}

bar
echo $a
```

Static vs. Dynamic Scope

Most modern languages use static scoping.

Easier to understand, harder to break programs.

Advantage of dynamic scoping: ability to change environment.

A way to surreptitiously pass additional parameters.

Symbol Tables

- A symbol table is a data structure that tracks the current bindings of identifier
- Scopes are nested: keep tracks of the current/open/closed scopes.
- Implementation: one symbol table for each scope.

Symbol Tables by Example: C-style

Implementing C-style scope (during walk over AST):

```
int x;
int main() {
  int a = 1;
  int b = 1; {
    float b = 2;
    for (int i = 0; i < b; i++) {
      int b = i;
      ...
    }
  }
  b + x;
}
```

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- Reach a declaration: Add entry to current table

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```

$x \mapsto$ **int**

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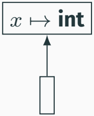

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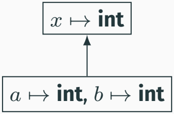

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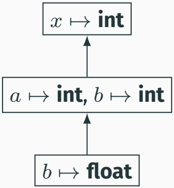

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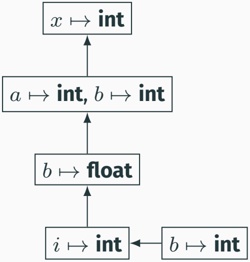
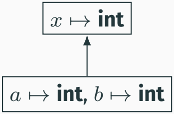


Symbol Tables by Example: C-style

Implementing C-style scope (during walk over AST):

- Reach a declaration: Add entry to current table
- Enter a "block": New symbol table; point to previous
- Reach an identifier: lookup in chain of tables
- Leave a block: Local symbol table disappears

```
int x;
int main() {
  int a = 1;
  int b = 1; {
    float b = 2;
    for (int i = 0; i < b; i++) {
      int b = i;
      ...
    }
  }
  b + x;
}
```



Types - What operations are allowed?

Types

A restriction on the possible interpretations of a segment of memory or other program construct.

Two uses:

Safety: avoids data being treated as something it isn't

Optimization: eliminates certain runtime decisions

Safety - Why do we need types?

Certain operations are legal for certain types.

```
int a = 1, b = 2;
return a + b;
```

```
int a[10], b[10];
return a + b;
```

Optimization - Why do we need types?

C was designed for efficiency: basic types are whatever is most efficient for the target processor.

On an (32-bit) ARM processor,

```
char c;            /* 8-bit binary */

short d;           /* 16-bit two's-complement binary */
unsigned short d;  /* 16-bit binary */

int a;             /* 32-bit two's-complement binary */
unsigned int b;    /* 32-bit binary */

float f;           /* 32-bit IEEE 754 floating-point */
double g;          /* 64-bit IEEE 754 floating-point */
```

Misbehaving Floating-Point Numbers

$1e20 + 1e\text{-}20 = 1e20$

$1e\text{-}20 \ll 1e20$

Misbehaving Floating-Point Numbers

$1\text{e}20 + 1\text{e-}20 = 1\text{e}20$

$1\text{e-}20 \ll 1\text{e}20$

$(1 + 9\text{e-}7) + 9\text{e-}7 \neq 1 + (9\text{e-}7 + 9\text{e-}7)$

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$1.00001(1.000001 - 1) \neq 1.00001 \cdot 1.000001 - 1.00001 \cdot 1$

$1.00001 \cdot 1.000001 = 1.0000100001$ requires too much intermediate precision.

What's Going On?

Floating-point numbers are represented using an exponent/significand format:

$$\underbrace{1}_{S}\ \underbrace{10000001}_{\text{8-bit exponent } E}\ \underbrace{01100000000000000000000}_{\text{23-bit significand } M}$$

$$= -1^S \times (1.0 + 0.M) \times 2^{E-bias}$$

$$= -1.011_2 \times 2^{129-127} = -1.375 \times 4 = -5.5.$$

What to remember:

$$\underbrace{1363.4568}_{\text{represented}}\underbrace{46353963456293}_{\text{rounded}}$$

What's Going On?

Results are often rounded:

$$\begin{array}{r} 1.00001000000 \\ \times 1.00000100000 \\ \hline 1.000011\underbrace{00001}_{\text{rounded}} \end{array}$$

When $b \approx -c$, $b + c$ is small, so $ab + ac \neq a(b + c)$ because precision is lost when ab is calculated.

Moral: Be aware of floating-point number properties when writing complex expressions.

Type Systems

Type Systems

- A language’s type system specifies which operations are valid for which types.
- The goal of type checking is to ensure that operations are used with the correct types.
- Three kinds of languages:

Type Systems

- A language's type system specifies which operations are valid for which types.
- The goal of type checking is to ensure that operations are used with the correct types.
- Three kinds of languages:
    - Statically typed: All or almost all checking of types is done as part of compilation (C, Java)
    - Dynamically typed: Almost all checking of types is done as part of program execution (Python)
    - Untyped: No type checking (machine code)

Statically-Typed Languages

Statically-typed: compiler can determine types. Variables have a type.

Dynamically-typed: types determined at run time. Runtime objects have a type.

Is Java statically-typed?

```
class Foo {
   public void x() { ... }
}

class Bar extends Foo {
   public void x() { ... }
}

void baz(Foo f) {
  f.x();
}
```

Strongly-typed Languages

Strongly-typed: the type of a value does not change in unexpected ways.

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```
float g;
union { float f; int i } u;
u.i = 3;
g = u.f + 3.14159; /* u.f is meaningless */
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Is Java strongly-typed?

What about Python?

Type Checking and Type Inference

- Type Checking is the process of verifying fully typed programs.
- Type Inference is the process of filling in missing type information.
- Inference Rules: formalism for type checking and inference.

Inference Rules

Inference rules have the form If Hypotheses are true, then Conclusion is true

$$\frac{\vdash \text{Hypothesis}_1 \qquad \vdash \text{Hypothesis}_2}{\vdash \text{Conclusion}}$$

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Typing rules for int:

$$\frac{}{\vdash \text{NUMBER} : \textbf{int}}$$

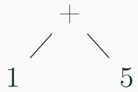
$$\frac{\vdash \text{expr}_1 : \textbf{int} \qquad \vdash \text{expr}_2 : \textbf{int}}{\vdash \text{expr}_1 + \text{expr}_2 : \textbf{int}}$$

Type checking computes via reasoning

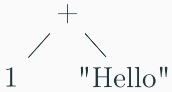
How To Check Expressions: Depth-first AST Walk

check: node $\rightarrow$ typedNode

```
1 + 5
```




```
1 + "Hello"
```



check($+$)

check(1) = 1 : int

check(5) = 5 : int

int $+$ int = int

= 1 $+$ 5 : int

How To Check Expressions: Depth-first AST Walk

check: node $\rightarrow$ typedNode

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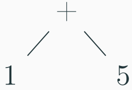


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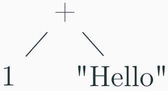

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check(1) = 1 : int

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int $+$ int = int

= 1 $+$ 5 : int

check(+)

check(1) = 1 : int

check(“Hello”) = “Hello” : string

FAIL: Can’t add int and string

How To Check Symbols?

What is the type of a variable reference?

$$\frac{x \text{ is a symbol}}{\vdash x :?}$$

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The local, structural rule does not carry enough information to give x a type.

Solution: Type Environment

Put more information in the rules!

A type environment gives types for free variables .

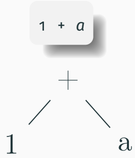
$$\frac{}{\mathcal{E} \vdash \text{NUMBER} : \ \textbf{int}}$$

$$\frac{\mathcal{E}(x) = \textbf{T}}{\mathcal{E} \vdash x : \ \textbf{T}}$$

$$\frac{\mathcal{E} \vdash \text{expr}_1 : \ \textbf{int} \qquad \mathcal{E} \vdash \text{expr}_2 : \ \textbf{int}}{\mathcal{E} \vdash \text{expr}_1 + \text{expr}_2 : \ \textbf{int}}$$

How To Check Symbols

check: environment $\rightarrow$ node $\rightarrow$ typedNode



check(+, E)

check(1, E) = 1 : int

check(a, E) = a : E.lookup(a) = a : int

int + int = int

= 1 $+$ a : int

The environment provides a “symbol table” that holds information about each in-scope symbol.

The Type of Types

Need an OCaml type to represent the type of something in your language.

For NanoC, it's simple (from ast.ml):

```
type typ = Int | Bool | Float | Void
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For a language with integer, structures, arrays, and exceptions:

```
type ty = (* can't call it "type" since that's reserved *)
    Void
  | Int
  | Array of ty * int                          (*type, sizes*)
  | Exception of string
  | Struct of string * ((string*ty) array) (*name, fields*)
```

Implementing a Symbol Table and Lookup

```
module StringMap = Map.Make(String)

type symbol_table = {
  (* Variables bound in current block *)
  variables : ty StringMap.t
  (* Enclosing scope *)
  parent : symbol_table option;
}
```

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module StringMap = Map.Make(String)

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```

```
let rec find_variable (scope : symbol_table) name =
  try
    (* Try to find binding in nearest block *)
    StringMap.find name scope.variables
  with Not_found -> (* Try looking in outer blocks *)
    match scope.parent with
      Some(parent) -> find_variable parent name
    | _ -> raise Not_found
```

check: ast $\rightarrow$ sast

Converts a raw AST to a "semantically checked AST"

Names and types resolved

AST:

```
type expr =
    Literal of int
  | Id of string
  | Call of string * expr list
  | ...
```

$\Downarrow$

SAST:

```
type expr_detail =
   SLiteral of int
 | SId of string
 | SCall of string * sexpr list
 | ...

type sexpr = expr_detail * ty
```