Lecture 06 – Semantic Analysis

THEORY OF COMPILATION

Eran Yahav

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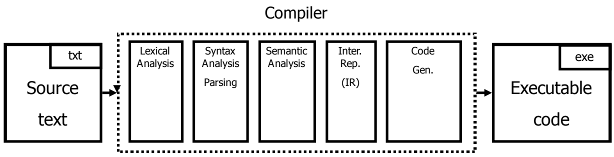

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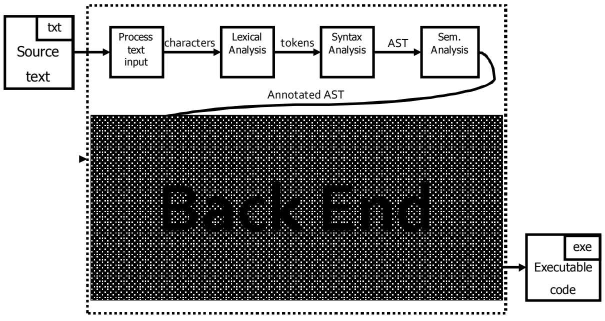
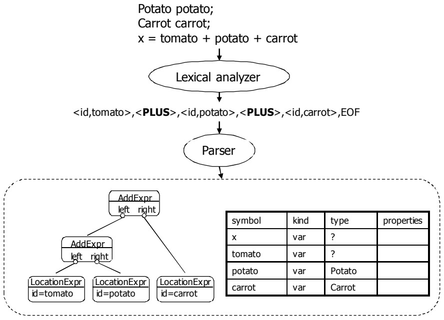


What we want



symbol	kind	type	properties
x	var	?	
tomato	var	?	
potato	var	Potato	
carrot	var	Carrot	

tomato is undefined

potato used before initialized

Cannot add Potato and Carrot

Contextual Analysis

- Often called "Semantic analysis"
- Properties that cannot be formulated via CFG
  - Type checking
  - Declare before use
    - Identifying the same word "w" re-appearing – wbw
  - Initialization
  - …
- Properties that are hard to formulate via CFG
  - "break" only appears inside a loop
  - …
- Processing of the AST

Contextual Analysis

- Identification
  - Gather information about each named item in the program
  - e.g., what is the declaration for each usage
- Context checking
  - Type checking
  - e.g., the condition in an if-statement is a Boolean

Identification

```
month : integer RANGE [1..12];
…
month := 1;
while (month <= 12) {
  print(month_name[month]);
  month : = month + 1;
}
```

- Forward references?
- Languages that don't require declarations?

Symbol table

```
month : integer RANGE [1..12];
…
month := 1;
while (month <= 12) {
  print(month_name[month]);
  month : = month + 1;
}
```

name	pos	type	…
month	1	RANGE[1..12]	
month_name	…	…	
…			

- A table containing information about identifiers in the program
- Single entry for each named item

Not so fast…

```
struct one_int {
  int i;
} i;

main() {
 i.i = 42;
 int t = i.i;
 printf("%d",t);
}
```

A struct field named i

A struct variable named i

Assignment to the "i" field of struct "i"

Reading the "i" field of struct "i"

Not so fast…

```
struct one_int {
  int i;
} i;

main() {
 i.i = 42;
 int t = i.i;
 printf("%d",t);
 {
  int i = 73;
  printf("%d",i);
 }
}
```

A struct field named i

A struct variable named i

Assignment to the "i" field of struct "i"

Reading the "i" field of struct "i"

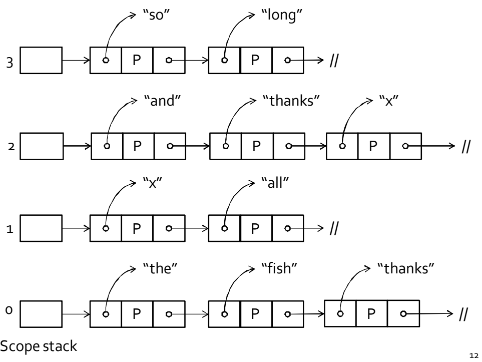
int variable named "i"

Scopes

- Typically stack structured scopes
- Scope entry
  - push new empty scope element
- Scope exit
  - pop scope element and discard its content
- Identifier declaration
  - identifier created inside top scope
- Identifier Lookup
  - Search for identifier top-down in scope stack

Scope-structured symbol table

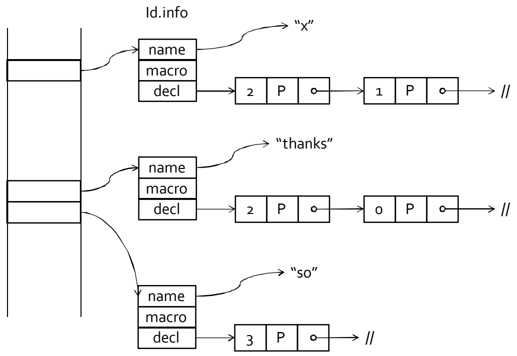
```
{
int the=1;
int fish=2;
Int thanks=3;
{
 int x = 42;
 int all = 73;
  {
…
  }
 }
}
```



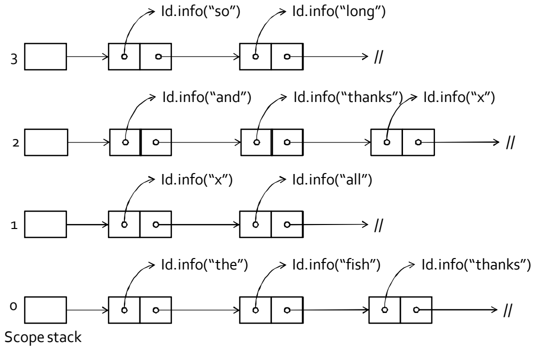
Scope and symbol table

- Scope x Identifier -> properties
    - Expensive lookup
- A better solution
    - hash table over identifiers

Hash-table based Symbol Table



Scope info



(now just pointers to the corresponding record in the symbol table)

Remember lexing/parsing?

- How did we know to always map an identifier to the same token?

Semantic Checks

- Scope rules
  - Use symbol table to check that
    - Identifiers defined before used
    - No multiple definition of same identifier
    - Program conforms to scope rules
- Type checking
  - Check that types in the program are consistent
  - How?

Types

- What is a type?
  - Simplest answer: a set of values
  - Integers, real numbers, booleans, …
- Why do we care?
  - Safety
    - Guarantee that certain errors cannot occur at runtime
  - Abstraction
    - Hide implementation details
  - Documentation
  - Optimization

Type System (textbook definition)

> *"A type system is a tractable syntactic method for proving the absence of certain program behaviors by classifying phrases according to the kinds of values they compute"*

-- Types and Programming Languages
/ Benjamin C. Pierce

Type System

- A type system of a programming language is a way to define how "good" program behave
  - Good programs = well-typed programs
  - Bad programs = not well typed
- Type checking
  - Static typing – most checking at compile time
  - Dynamic typing – most checking at runtime
- Type inference
  - Automatically infer types for a program (or show that there is no valid typing)

Static typing vs. dynamic typing

- Static type checking is conservative
  - Any program that is determined to be well-typed is free from certain kinds of errors
  - May reject programs that cannot be statically determined as well typed
  - Why?
- Dynamic type checking
  - May accept more programs as valid (runtime info)
  - Errors not caught at compile time
  - Runtime cost

Type Checking

- Type rules specify
  - which types can be combined with certain operator
  - Assignment of expression to variable
  - Formal and actual parameters of a method call
- Examples

string string
"drive" + "drink"
string

int string
42 + "the answer"
ERROR

Type Checking Rules

- Specify for each operator
  - Types of operands
  - Type of result
- Basic Types
  - Building blocks for the type system (type rules)
  - e.g., int, boolean, (sometimes) string
- Type Expressions
  - Array types
  - Function types
  - Record types / Classes

Typing Rules

If E1 has type int and E2 has type int,
then E1 + E2 has type int

$$\frac{E1 : int \qquad E2 : int}{E1 + E2 : int}$$

(Generally, also use a context A)

More Typing Rules (examples)

$$\frac{}{A \vdash \text{true} : \text{boolean}} \qquad \frac{}{A \vdash \text{false} : \text{boolean}}$$

$$\frac{}{A \vdash \textit{int-literal} : \text{int}} \qquad \frac{}{A \vdash \textit{string-literal} : \text{string}}$$

$$\frac{A \vdash E1 : \text{int} \qquad A \vdash E2 : \text{int}}{A \vdash E1\ \textit{op}\ E2 : \text{int}} \qquad \textit{op} \in \{ +, -, /, *, \% \}$$

$$\frac{A \vdash E1 : \text{int} \qquad A \vdash E2 : \text{int}}{A \vdash E1\ \textit{rop}\ E2 : \text{boolean}} \qquad \textit{rop} \in \{ <=, <, >, >= \}$$

$$\frac{A \vdash E1 : T \qquad A \vdash E2 : T}{A \vdash E1\ \textit{rop}\ E2 : \text{boolean}} \qquad \textit{rop} \in \{ ==, != \}$$

And Even More Typing Rules

$$\frac{A \vdash E1 : \text{boolean} \qquad A \vdash E2 : \text{boolean}}{A \vdash E1\ \textit{lop}\ E2 : \text{boolean}} \qquad \textit{lop} \in \{ \&\&, || \}$$

$$\frac{A \vdash E1 : \text{int}}{A \vdash \mathbf{-}\ E1 : \text{int}} \qquad \frac{A \vdash E1 : \text{boolean}}{A \vdash \mathbf{!}\ E1 : \text{boolean}}$$

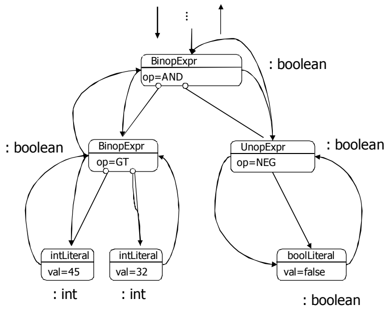
$$\frac{A \vdash E1 : T[]}{A \vdash E1.\text{length} : \text{int}} \qquad \frac{A \vdash E1 : T[] \qquad A \vdash E2 : \text{int}}{A \vdash E1[E2] : T} \qquad \frac{A \vdash E1 : \text{int}}{A \vdash \text{new } T[E1] : T[]}$$

$$\frac{A \vdash T \backslash\text{in } C}{A \vdash \text{new } T() : T} \qquad \frac{\text{id} : T \in A}{A \vdash \text{id} : T}$$

Type Checking

- Traverse AST and assign types for AST nodes
  - Use typing rules to compute node types
- Alternative: type-check during parsing
  - More complicated alternative
  - But naturally also more efficient

Example



$$\frac{A \vdash E1 : \text{boolean} \qquad A \vdash E2 : \text{boolean}}{A \vdash E1\ \textit{lop}\ E2 : \text{boolean}}$$

$\textit{lop} \in \{ \&\&, || \}$

$$\frac{A \vdash E1 : \text{boolean}}{A \vdash !E1 : \text{boolean}}$$

$$\frac{A \vdash E1 : \text{int} \qquad A \vdash E2 : \text{int}}{A \vdash E1\ \textit{rop}\ E2 : \text{boolean}}$$

$\textit{rop} \in \{ <=, <, >, >= \}$

$$\frac{}{A \vdash \text{false} : \text{boolean}}$$

$$\frac{}{A \vdash \textit{int-literal} : \text{int}}$$

45 > 32 && !false

Type Declarations

- So far, we ignored the fact that types can also be declared

```
TYPE Int_Array = ARRAY [Integer 1..42] OF Integer;     (explicitly)
```

```
Var a : ARRAY [Integer 1..42] OF Real;            (anonymously)
```

Type Declarations

```
Var a : ARRAY [Integer 1..42] OF Real;
```

⇩

```
TYPE #type01_in_line_73 = ARRAY [Integer 1..42] OF Real;
Var a : #type01_in_line_73;
```

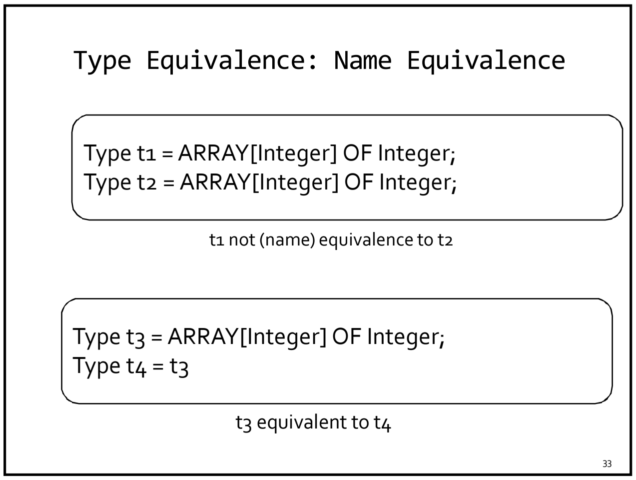
Forward References

```
TYPE Ptr_List_Entry = POINTER TO List_Entry;
TYPE List_Entry =
  RECORD
    Element : Integer;
    Next : Ptr_List_Entry;
  END RECORD;
```

- Forward references must be resolved
  - A forward references added to the symbol table as forward reference, and later updated when type declaration is met
  - At the end of scope, must check that all forward references have been resolved
  - Check must be added for circularity

Type Table

- All types in a compilation unit are collected in a type table
- For each type, its table entry contains:
  - Type constructor: basic, record, array, pointer,…
  - Size and alignment requirements
    - to be used later in code generation
  - Types of components (if applicable)
    - e.g., types of record fields



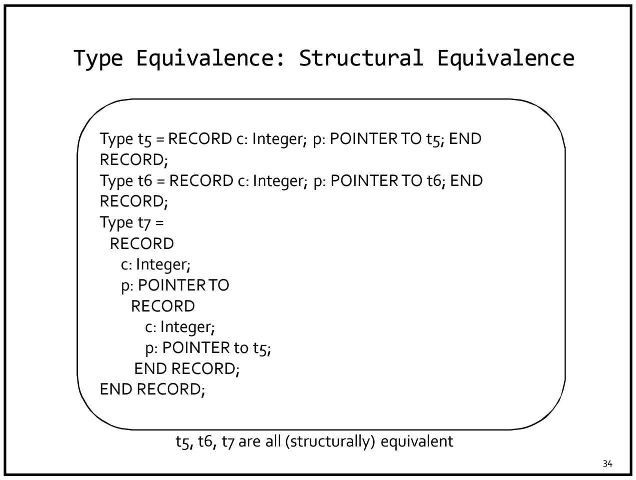
Type Equivalence: Name Equivalence

```
Type t1 = ARRAY[Integer] OF Integer;
Type t2 = ARRAY[Integer] OF Integer;
```

t1 not (name) equivalence to t2

```
Type t3 = ARRAY[Integer] OF Integer;
Type t4 = t3
```

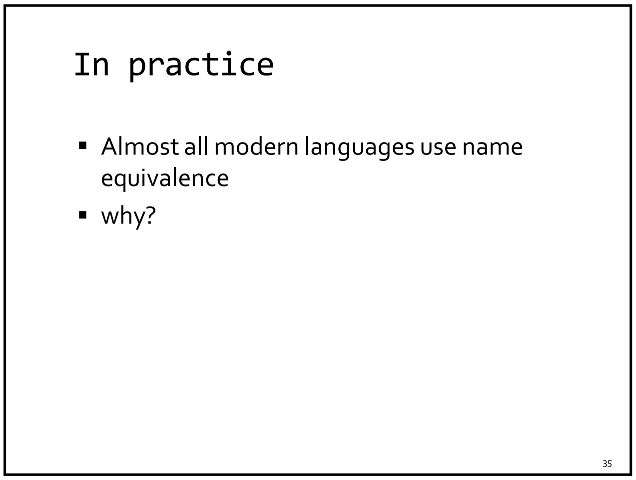
t3 equivalent to t4



Type Equivalence: Structural Equivalence

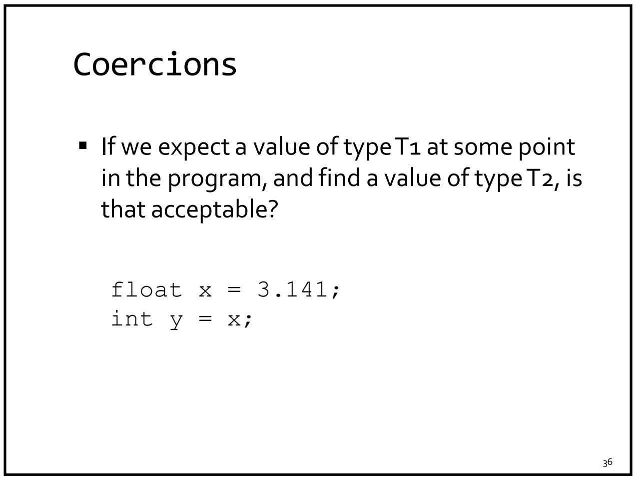
```
Type t5 = RECORD c: Integer; p: POINTER TO t5; END
RECORD;
Type t6 = RECORD c: Integer; p: POINTER TO t6; END
RECORD;
Type t7 =
  RECORD
    c: Integer;
    p: POINTER TO
      RECORD
        c: Integer;
        p: POINTER to t5;
      END RECORD;
END RECORD;
```

t5, t6, t7 are all (structurally) equivalent



In practice

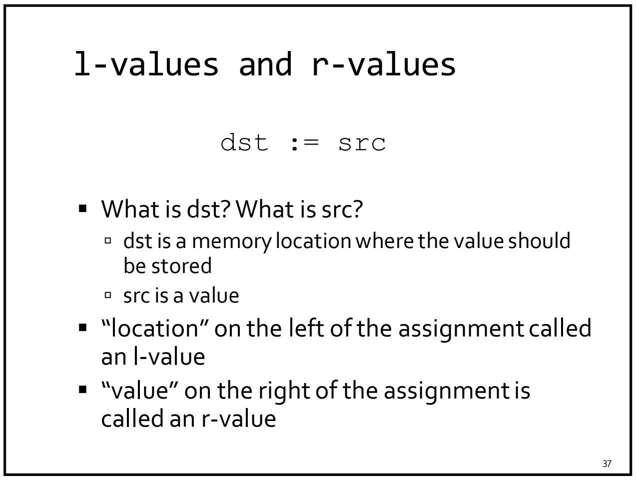
- Almost all modern languages use name equivalence
- why?



Coercions

- If we expect a value of type T1 at some point in the program, and find a value of type T2, is that acceptable?

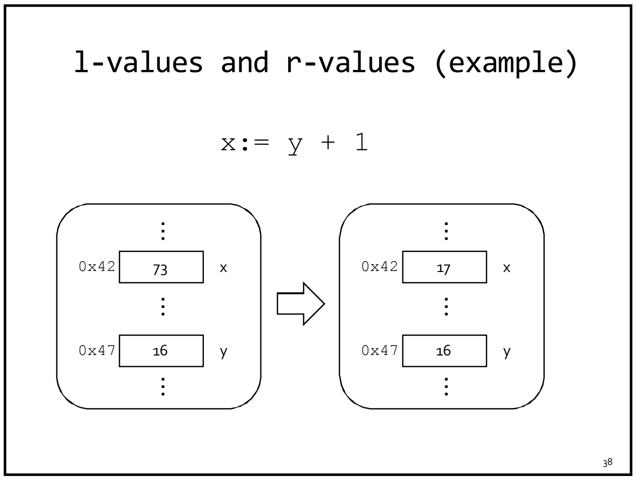
```
float x = 3.141;
int y = x;
```



l-values and r-values

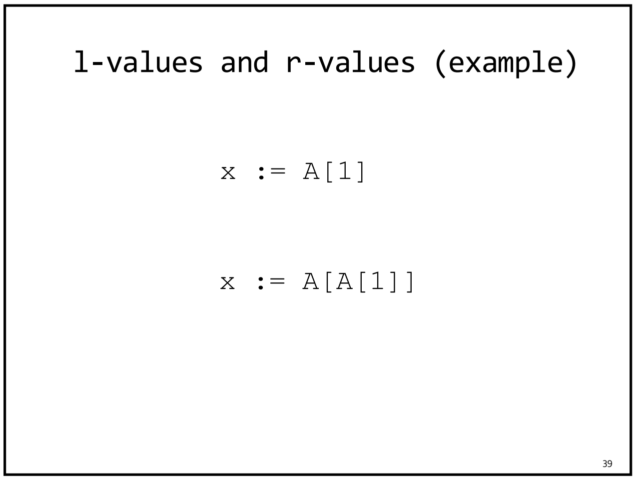
`dst := src`

- What is dst? What is src?
  - dst is a memory location where the value should be stored
  - src is a value
- “location” on the left of the assignment called an l-value
- “value” on the right of the assignment is called an r-value



l-values and r-values (example)

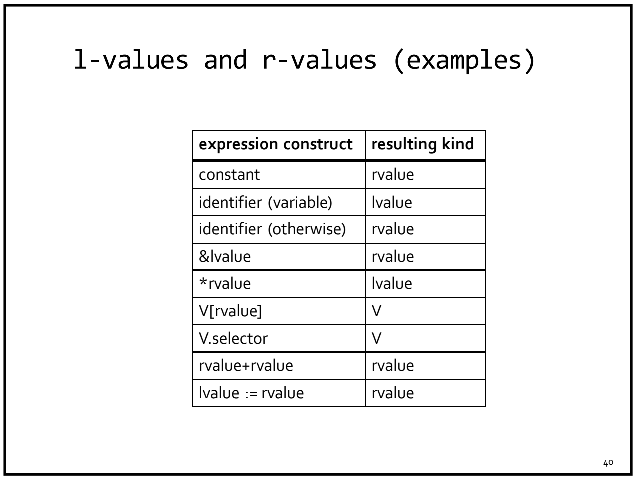
`x:= y + 1`



l-values and r-values (example)

`x := A[1]`

`x := A[A[1]]`



l-values and r-values (examples)

expression construct	resulting kind
constant	rvalue
identifier (variable)	lvalue
identifier (otherwise)	rvalue
&lvalue	rvalue
*rvalue	lvalue
V[rvalue]	V
V.selector	V
rvalue+rvalue	rvalue
lvalue := rvalue	rvalue

l-values and r-values

		expected	
		lvalue	**rvalue**
found	lvalue	-	deref
	rvalue	error	-

So far…

- Static correctness checking
  - Identification
  - Type checking
- Identification matches applied occurrences of identifier to its defining occurrence
- Type checking checks which type combinations are legal
- Each node in the AST of an expression represents either an l-value (location) or an r-value (value)

How does this magic happen?

- We probably need to go over the AST?
- how does this relate to the clean formalism of the parser?

Syntax Directed Translation

- Semantic attributes
  - Attributes attached to grammar symbols
- Semantic actions
  - (already mentioned when we did recursive descent)
  - How to update the attributes
- Attribute grammars

Attribute grammars

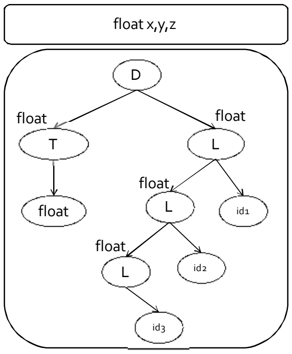
- Attributes
  - Every grammar symbol has attached attributes
    - Example: Expr.type
- Semantic actions
  - Every production rule can define how to assign values to attributes
    - Example:
      Expr ⟶ Expr + Term
      Expr.type = Expr1.type when (Expr1.type == Term.type)
      Error otherwise

Indexed symbols

- Add indexes to distinguish repeated grammar symbols
- Does not affect grammar
- Used in semantic actions

- Expr ⟶ Expr + Term
  Becomes
  Expr ⟶ Expr1 + Term

Example



Production	Semantic Rule
D ⟶ T L	L.in = T.type
T ⟶ int	T.type = integer
T ⟶ float	T.type = float
L ⟶ L1, id	L1.in = L.in addType(id.entry,L.in)
L ⟶ id	addType(id.entry,L.in)

Dependencies

- A semantic equation a = b1,…,bm requires computation of b1,…,bm to determine the value of a

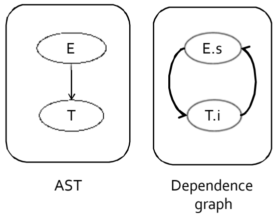
- The value of a depends on b1,…,bm
  - We write a ⟵ bi

Attribute Evaluation

- Build the AST
- Fill attributes of terminals with values derived from their representation
- Execute evaluation rules of the nodes to assign values until no new values can be assigned
  - In the right order such that
    - No attribute value is used before its available
    - Each attribute will get a value only once

Cycles

- Cycle in the dependence graph
- May not be able to compute attribute values



E.S = T.i
T.i = E.s + 1

Attribute Evaluation

- Build the AST
- Build dependency graph
- Compute evaluation order using topological ordering
- Execute evaluation rules based on topological ordering

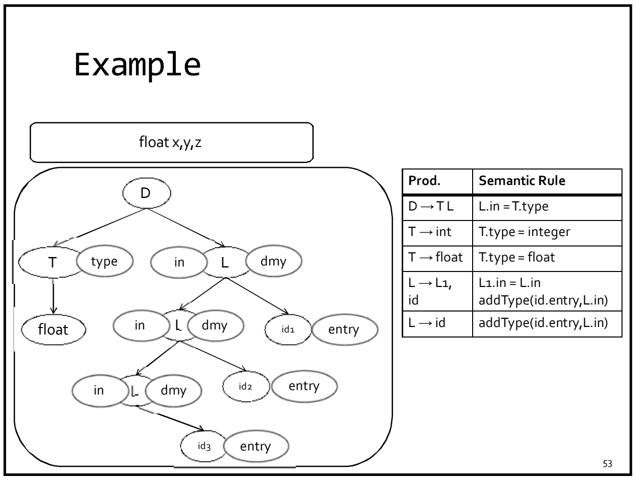
- Works as long as there are no cycles

Building Dependency Graph

- All semantic equations take the form

  attr1 = func1(attr1.1, attr1.2,…)
  attr2 = func2(attr2.1, attr2.2,…)

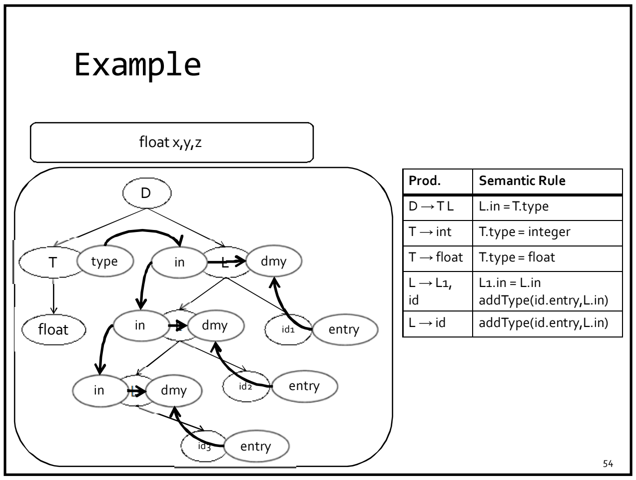
- Actions with side effects use a dummy attribute
- Build a directed dependency graph G
  - For every attribute a of a node n in the AST create a node n.a
  - For every node n in the AST and a semantic action of the form b = f(c1,c2,…ck) add edges of the form (ci,b)



Example

float x,y,z

Prod.	Semantic Rule
D → T L	L.in = T.type
T → int	T.type = integer
T → float	T.type = float
L → L1, id	L1.in = L.in addType(id.entry,L.in)
L → id	addType(id.entry,L.in)



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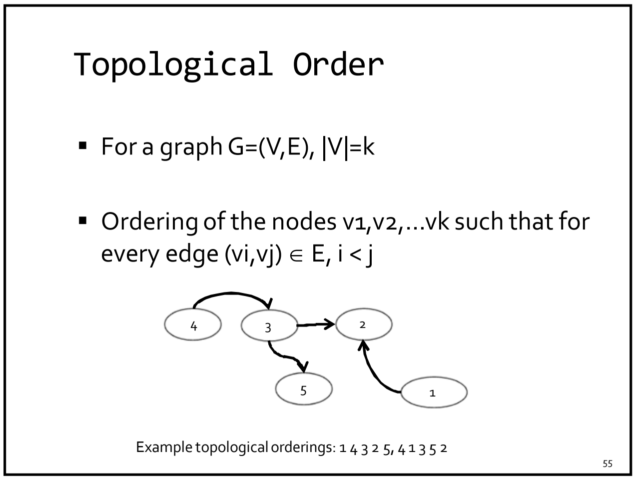
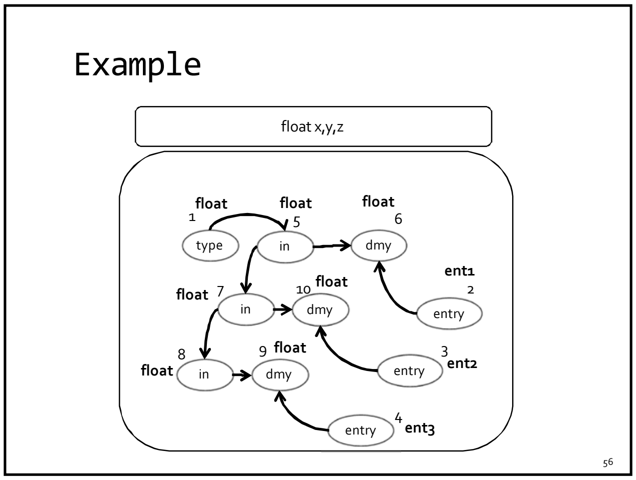


Topological Order

- For a graph G=(V,E), |V|=k
- Ordering of the nodes v1,v2,…vk such that for every edge (vi,vj) ∈ E, i < j

Example topological orderings: 1 4 3 2 5, 4 1 3 5 2



Example

float x,y,z

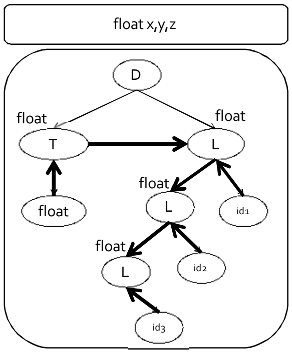
But what about cycles?

- For a given attribute grammar hard to detect if it has cyclic dependencies
    - Exponential cost
- Special classes of attribute grammars
    - Our "usual trick"
    - sacrifice generality for predictable performance

Inherited vs. Synthesized Attributes

- Synthesized attributes
    - Computed from children of a node
- Inherited attributes
    - Computed from parents and siblings of a node
- Attributes of tokens are technically considered as synthesized attributes

example



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T → float	T.type = float
L → L1, id	L1.in = L.in addType(id.entry,L.in)
L → id	addType(id.entry,L.in)

→ inherited

→ synthesized

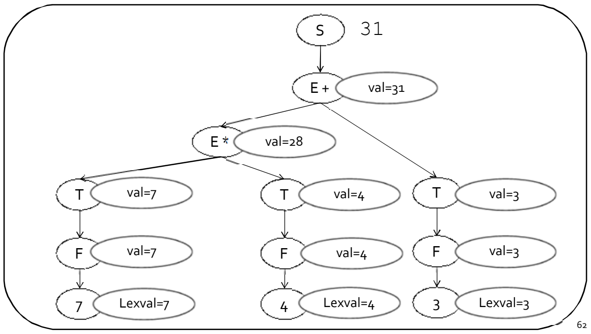
S-attributed Grammars

- Special class of attribute grammars
- Only uses synthesized attributes (S-attributed)
- No use of inherited attributes
- Can be computed by any bottom-up parser during parsing
- Attributes can be stored on the parsing stack
- Reduce operation computes the (synthesized) attribute from attributes of children

S-attributed Grammar: example

Production	Semantic Rule
S→ E ;	print(E.val)
E → E1 + T	E.val = E1.val + T.val
E → T	E.val = T.val
T → T1 * F	T.val = T1.val * F.val
T → F	T.val = F.val
F → (E)	F.val = E.val
F → digit	F.val = digit.lexval

example



L-attributed grammars

- L-attributed attribute grammar when every attribute in a production A → X1…Xn is
  - A synthesized attribute, or
  - An inherited attribute of Xj, 1 <= j <=n that only depends on
    - Attributes of X1…Xj-1 to the left of Xj, or
    - Inherited attributes of A

Summary

- Contextual analysis can move information between nodes in the AST
  - Even when they are not “local”
- Attribute grammars
  - Attach attributes and semantic actions to grammar
- Attribute evaluation
  - Build dependency graph, topological sort, evaluate
- Special classes with pre-determined evaluation order: S-attributed, L-attributed

The End