Compilation

0368-3133 (Semester A, 2013/14)

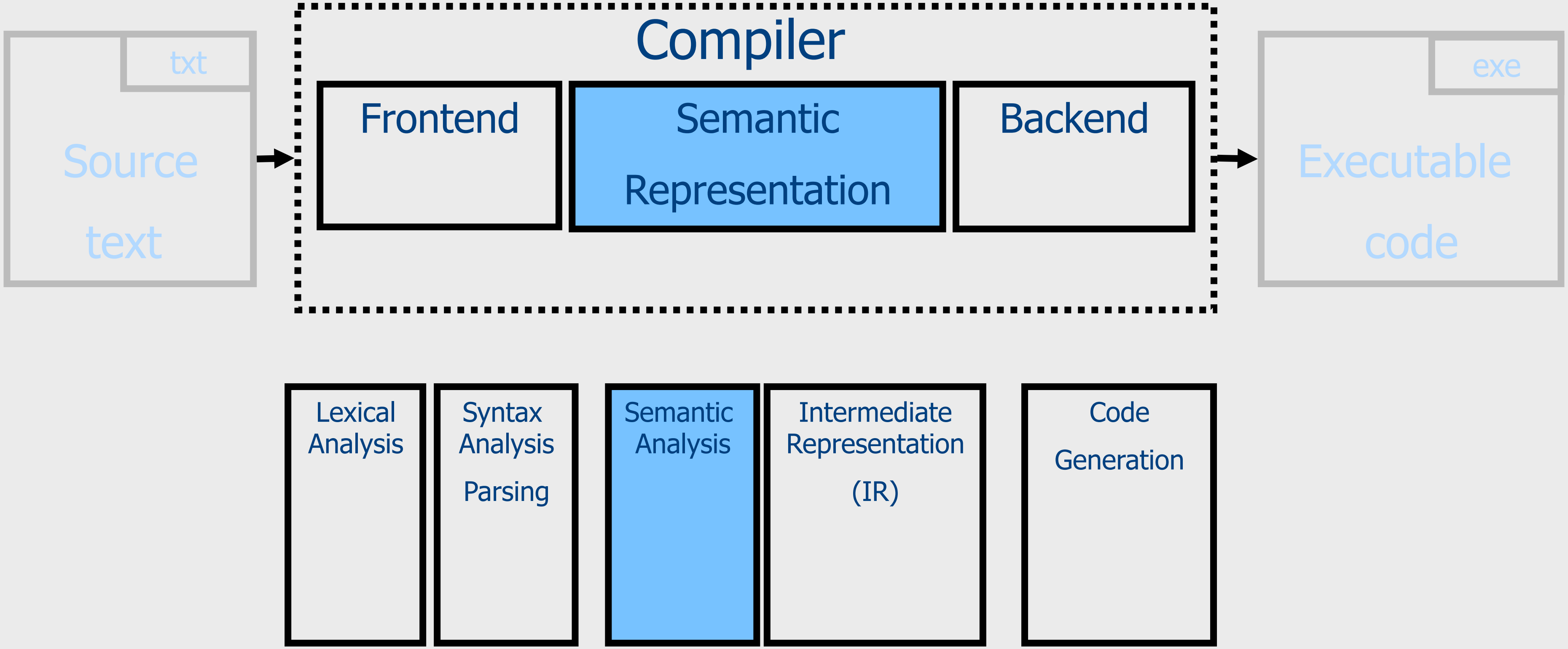
Lecture 6b: Context Analysis

(aka Semantic Analysis)

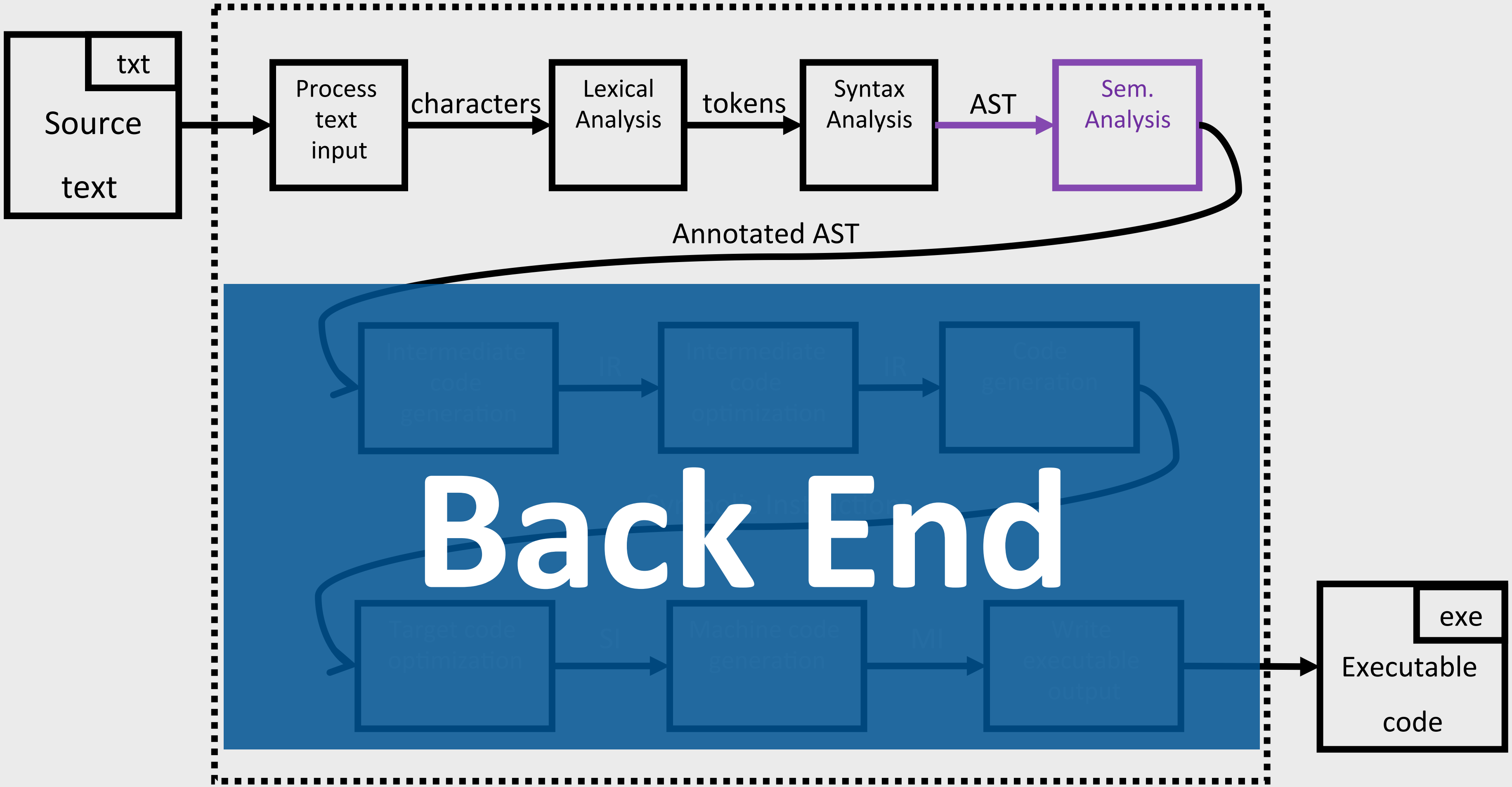
Noam Rinetzky

Slides credit: Mooly Sagiv and Eran Yahav

Conceptual Structure of a Compiler



You are here...


txt
Source
text
Process
text
input
characters
Lexical
Analysis
tokens
Syntax
Analysis
AST
Sem.
Analysis
Annotated AST
Back End
exe
Executable
code

Abstract Syntax Tree

- AST is a simplification of the parse tree
- Can be built by traversing the parse tree
  - E.g., using visitors
- Can be built directly during parsing
  - Add an action to perform on each production rule
  - Similarly to the way a parse tree is constructed

Building a Parse Tree

```
Node E() {
  result = new Node();
  result.name = "E";
  if (current ∈ {TRUE, FALSE}) // E → LIT
    result.addChild(LIT());
  else if (current == LPAREN)  // E → ( E OP E )
    result.addChild(match(LPAREN));
    result.addChild(E());
    result.addChild(OP());
    result.addChild(E());
    result.addChild(match(RPAREN));
  else if (current == NOT)         // E → not E
    result.addChild(match(NOT));
    result.addChild(E());
  else error;
    return result;
}
```

Building an AST

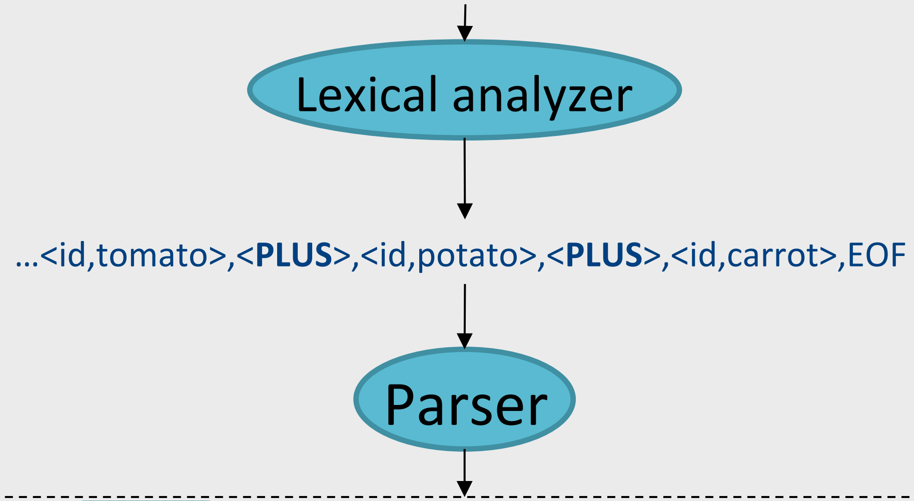
```
Node E() {
  if (current ∈ {TRUE, FALSE}) // E → LIT
    result = new LitNode(current);
  else if (current == LPAREN)  // E → ( E OP E )
    result = new BinNode();
    match(LPAREN);
    result.left = E();
    result.op = OP();
    result.right = E();
    match(RPAREN);
  else if (current == NOT)           // E → not E
    result = new NotNode();
    match(NOT));
    result.expr = E();
  else error;
  return result;
}
```

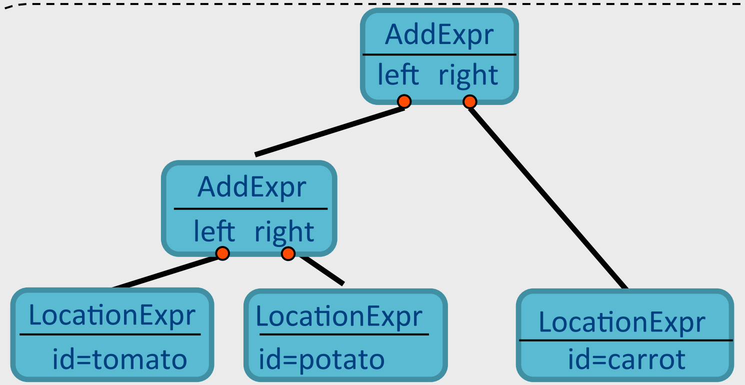
Abstract Syntax Tree

- The interface between the parser and the rest of the compiler
  - Separation of concerns
  - Reusable, modular and extensible
- The AST is defined by a context free grammar
  - The CFG of the AST can be ambiguous!
    - Is this a problem?
- Keep syntactic information
  - Why?

What we want

Potato potato;
Carrot carrot;
x = tomato + potato + carrot





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

Context Analysis

- Check properties contexts of in which constructs occur
  - 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

Context 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;
}
```

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"

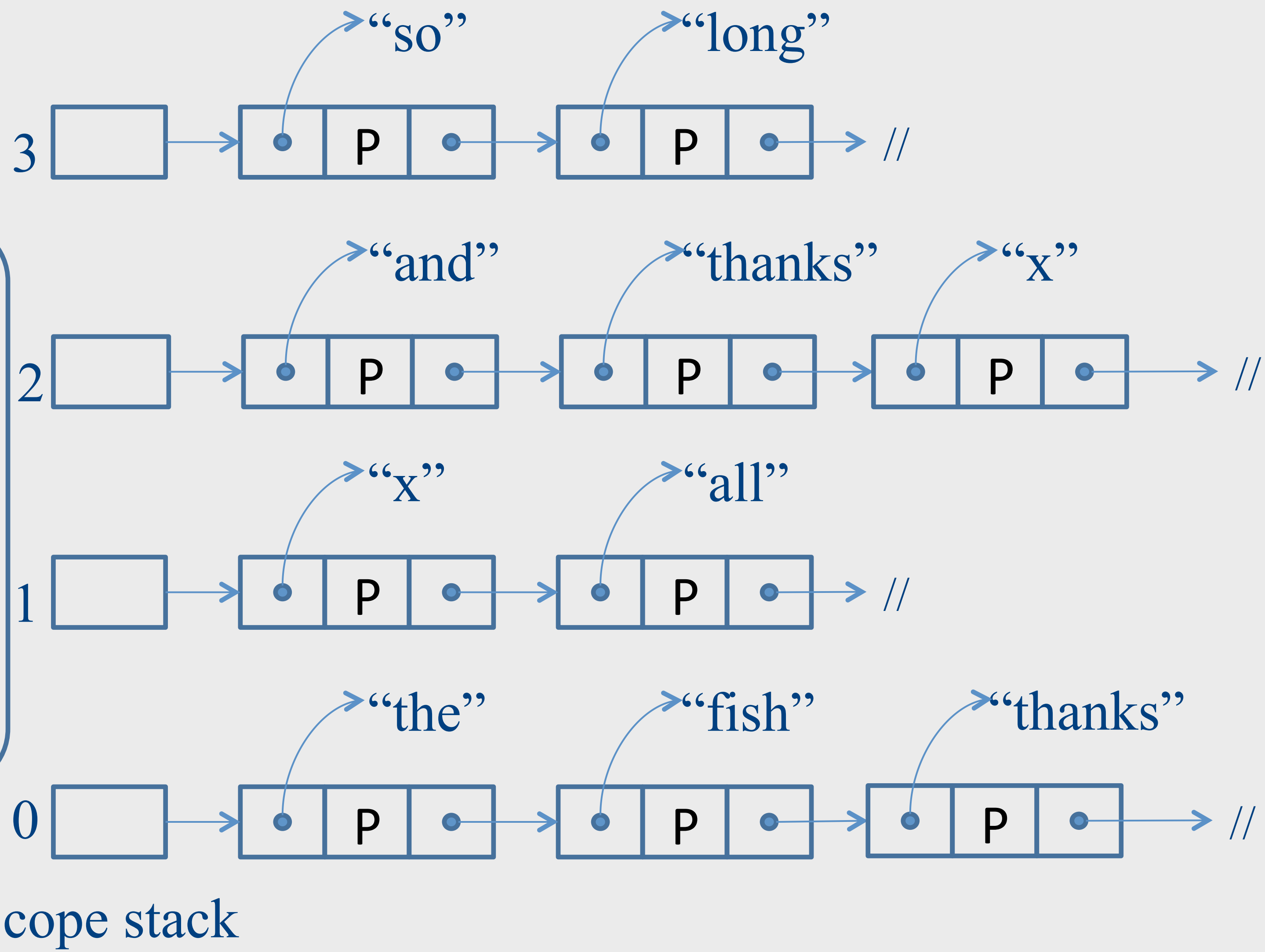
Scopes

- 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

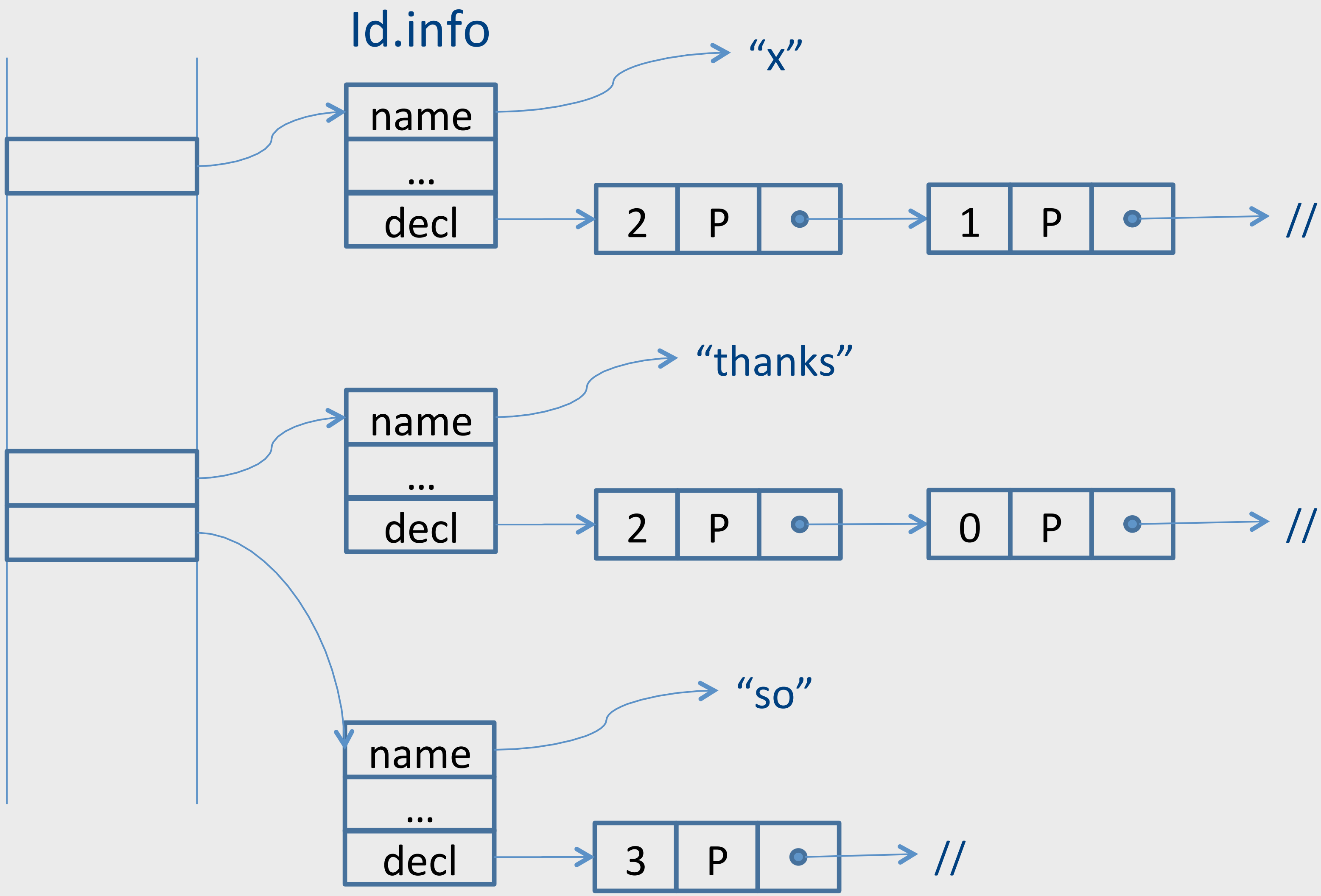
```
{
 int the=1;
 int fish=2;
 int thanks=3;
 {
  int x = 42;
  int all = 73;
  {
   …
  }
 }
}
```



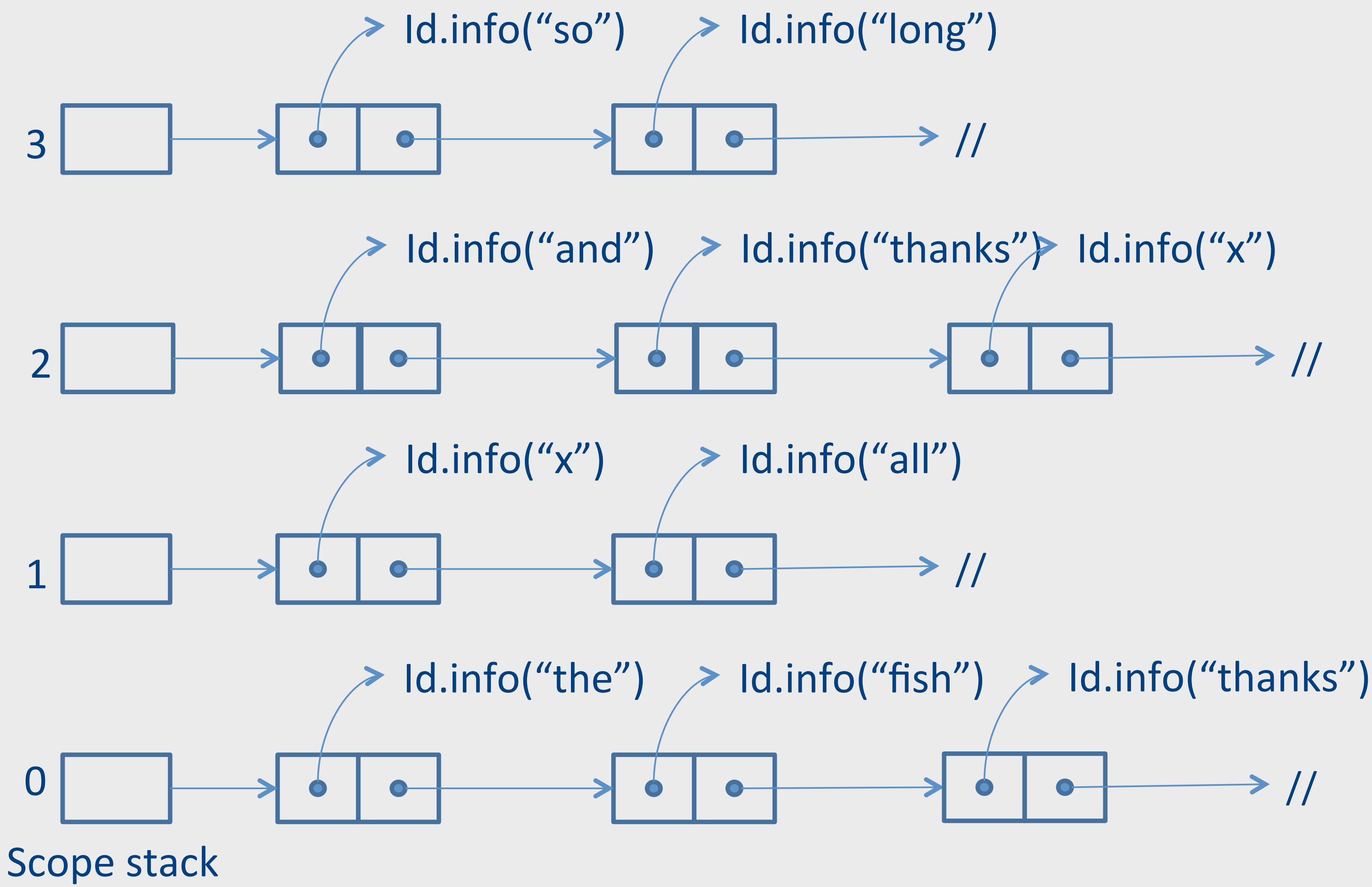
Scope and symbol table

- 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)

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

Semantic Checks

- Scope rules
  - Use symbol table to check that
    - Identifiers defined before used
    - No multiple definition of same identifier
    - …

- Type checking
  - Check that types in the program are consistent
    - How?
    - Why?

Types

- What is a type?
  - Simplest answer: a set of values + allowed operations
  - Integers, real numbers, booleans, …

- Why do we care?
  - Code generation: $1 := $1 + $2
  - 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
  - Why?

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

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

More Typing Rules (examples)

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

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

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

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

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

And Even More Typing Rules

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

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

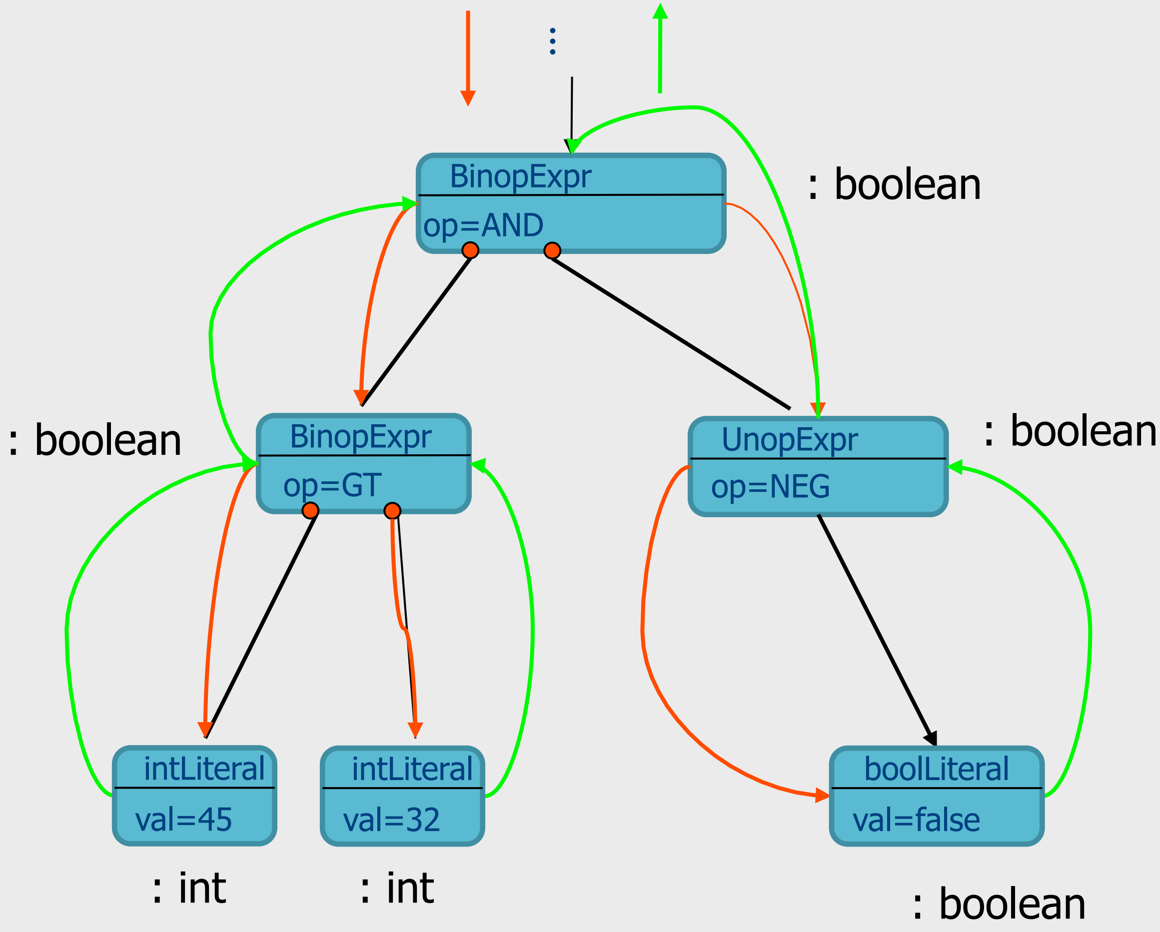
$$\frac{E1 : T[]}{E1.\text{length} : \text{int}} \qquad \frac{E1 : T[] \qquad E2 : \text{int}}{E1[E2] : T} \qquad \frac{E1 : \text{int}}{\text{new } T[E1] : T[]}$$

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



45 > 32 && !false

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

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

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

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

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

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

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

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;
```

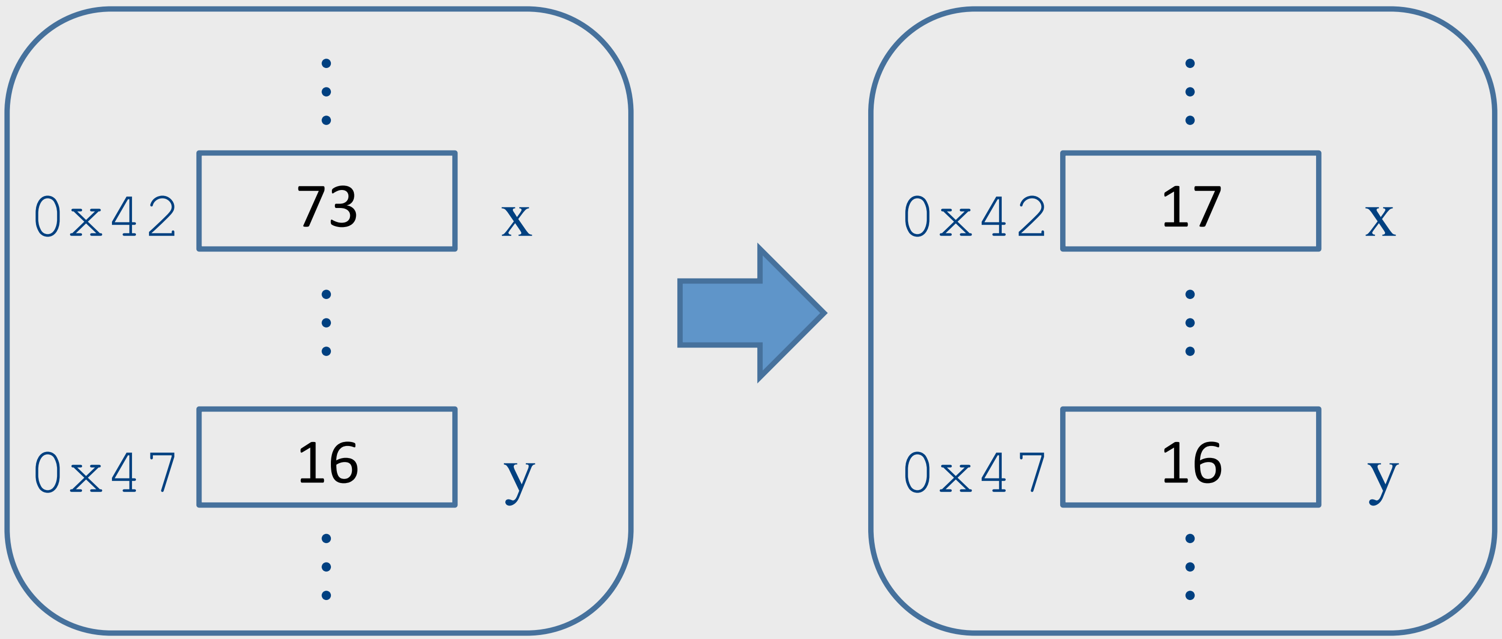
l-values and r-values

```
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

expected

found

	lvalue	rvalue
lvalue	-	deref
rvalue	error	-

So far…

- Static correctness checking
  - Identification
  - Type checking
- Identification matches applied occurrences of identifier to its defining occurrence
  - The symbol table maintains this information
- 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

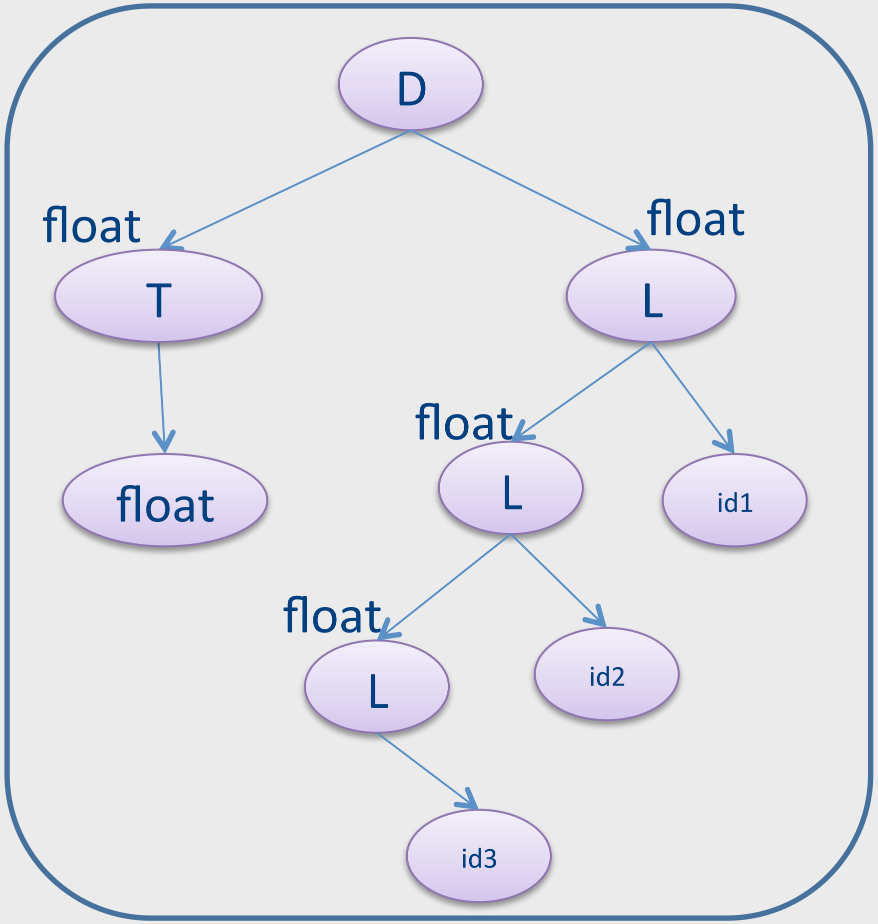
Indexed symbols

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

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

Example

float x,y,z



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)

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

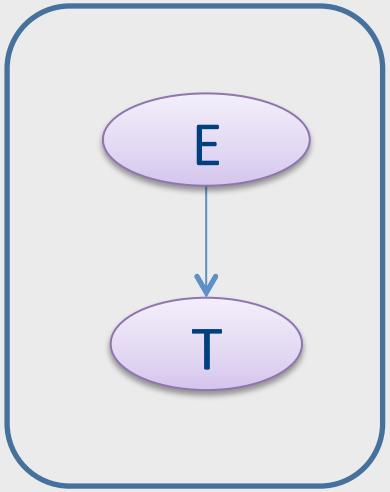
Dependencies

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

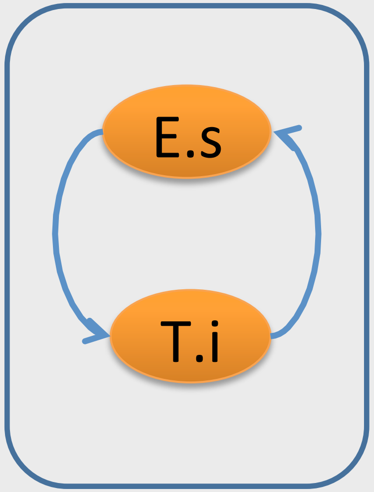
- The value of a depends on b1,…,bm
  – We write a ← bi

Cycles

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



AST



Dependence graph

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)

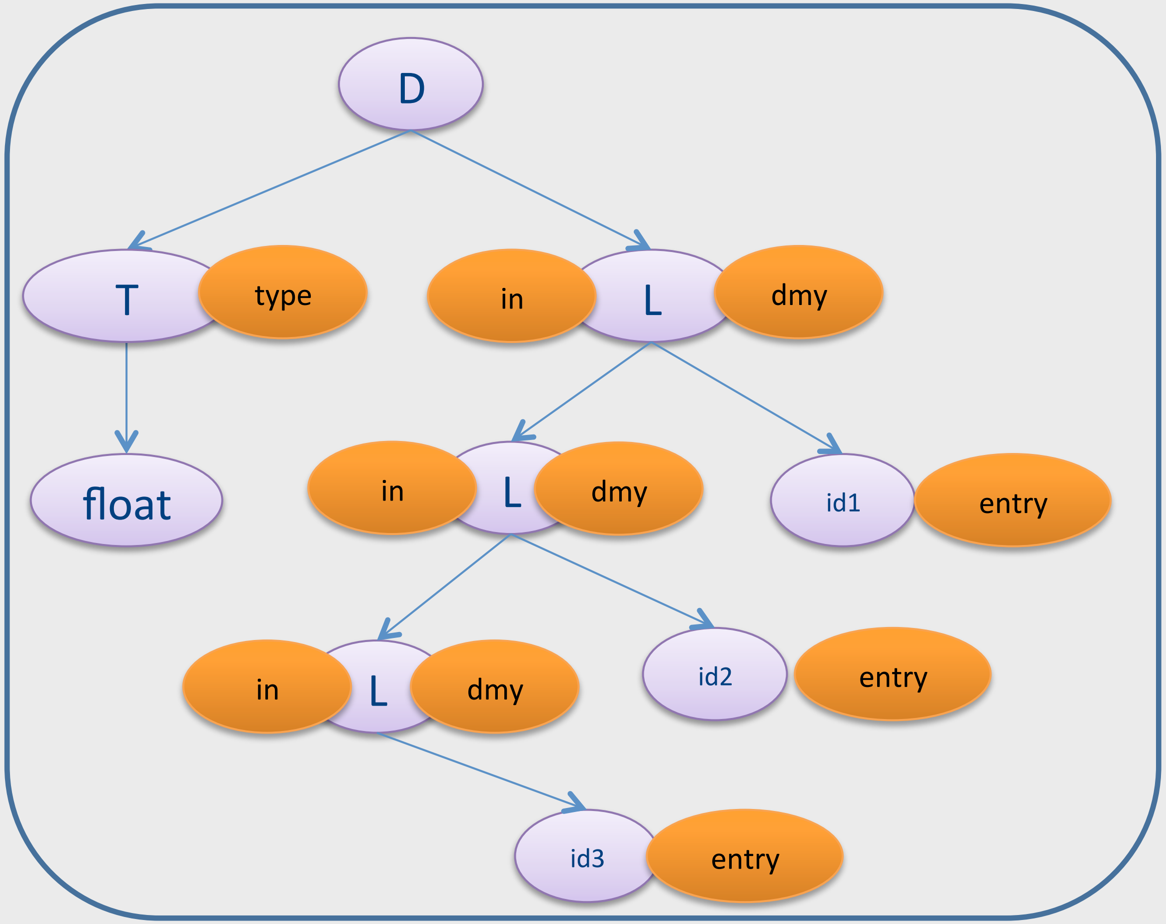
Production	Semantic Rule
D → T L	L.in = T.type
T → int	T.type = integer
T → float	T.type = float
L → L1, id	L1.in = L.in addType(id.entry,L.in)
L → id	addType(id.entry,L.in)

Convention:
Add dummy variables for side effects.

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 L.dmy = addType(id.entry,L.in)
L → id	L.dmy = addType(id.entry,L.in)

Example

float x,y,z



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Example

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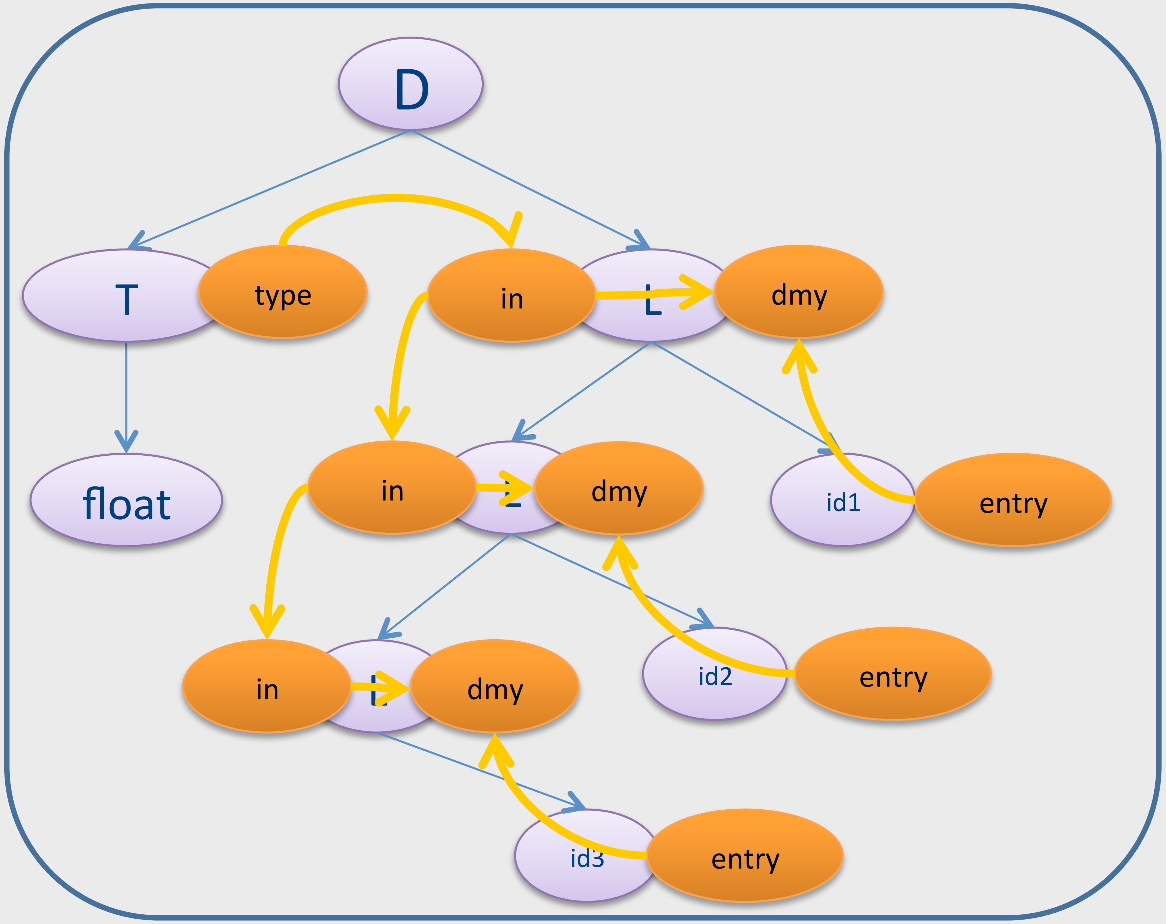

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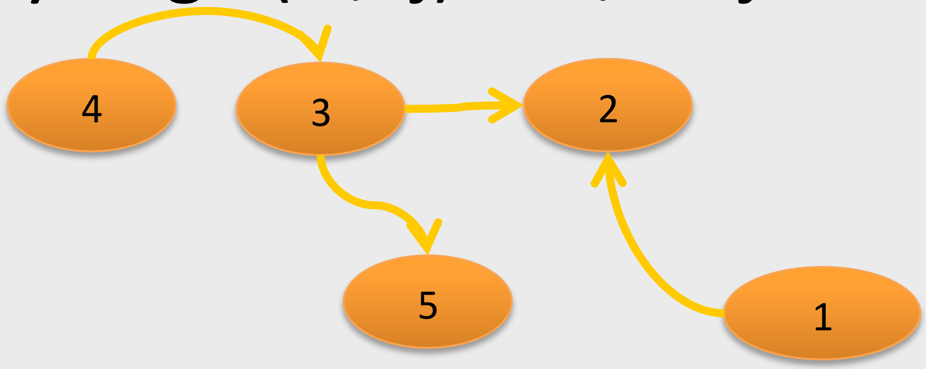
L ⟶ id	addType(id.entry,L.in)

Topological Order

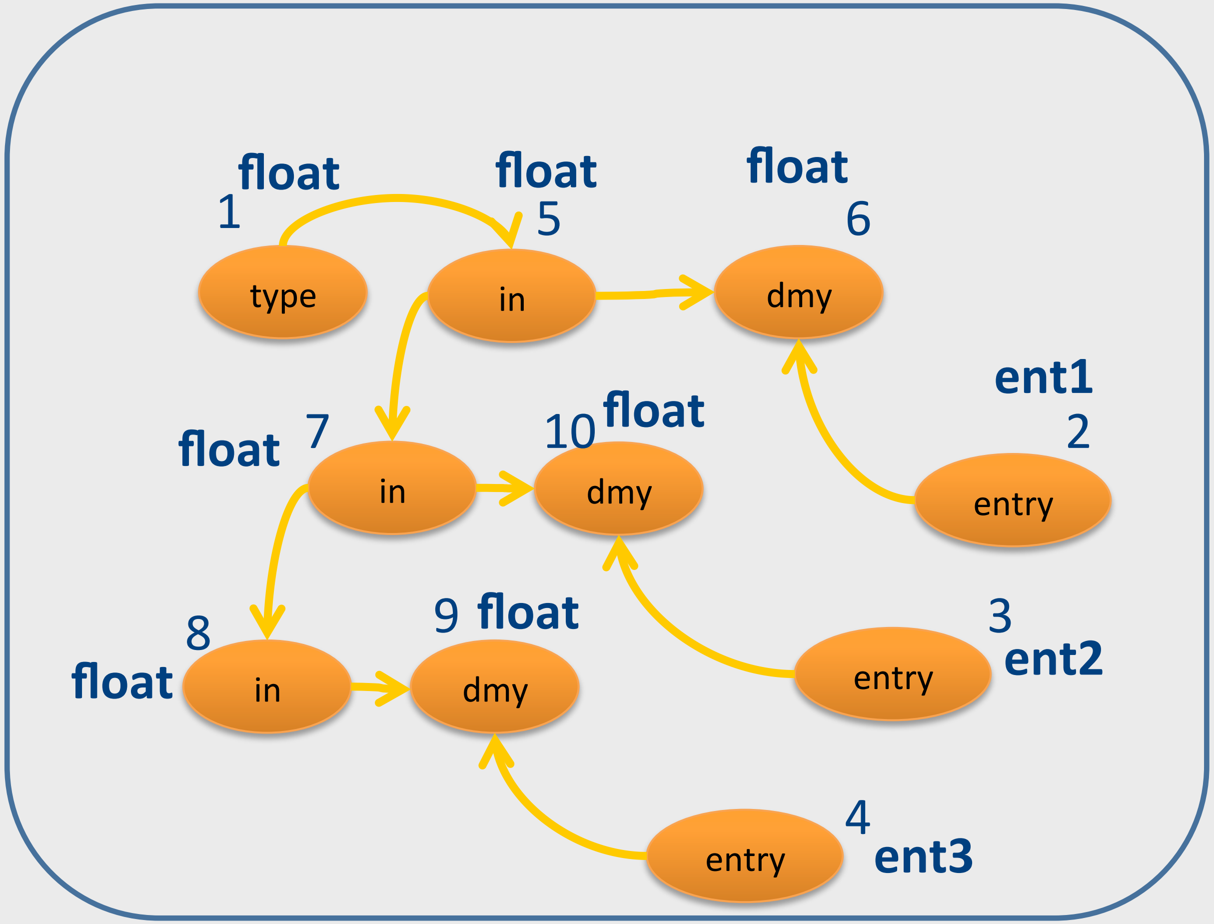
- For a graph G=(V,E), |V|=k
- Ordering of the nodes v1,v2,…vk such that for every edge (vi,vj) ∈ E, i < j



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

Example

float x,y,z



But what about cycles?

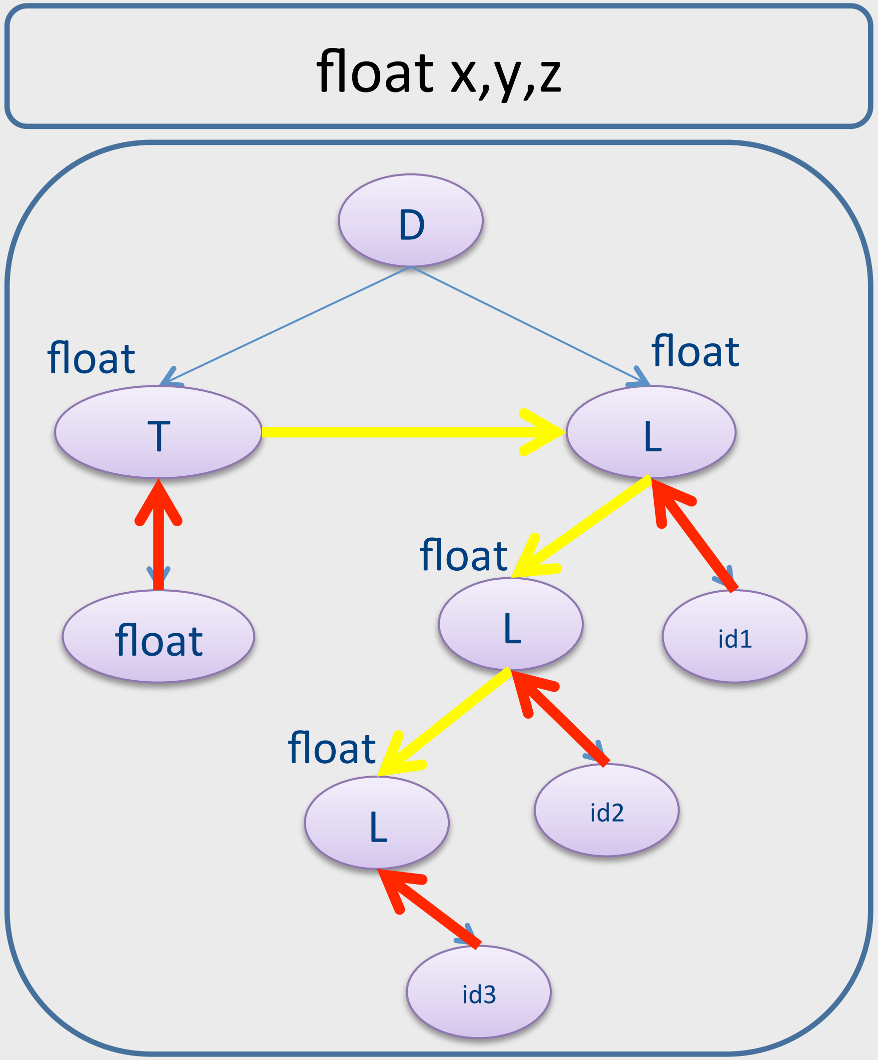
- For a given attribute grammar hard to detect if it has cyclic dependencies
  - Exponential cost
- Special classes of attribute grammars
  - Our "usual trick"
  - sacrifice generality for predictable performance

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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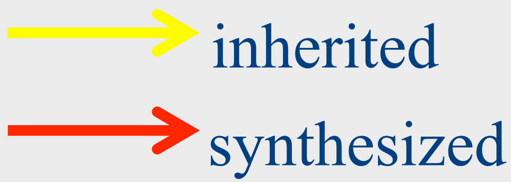


S-attributed Grammars

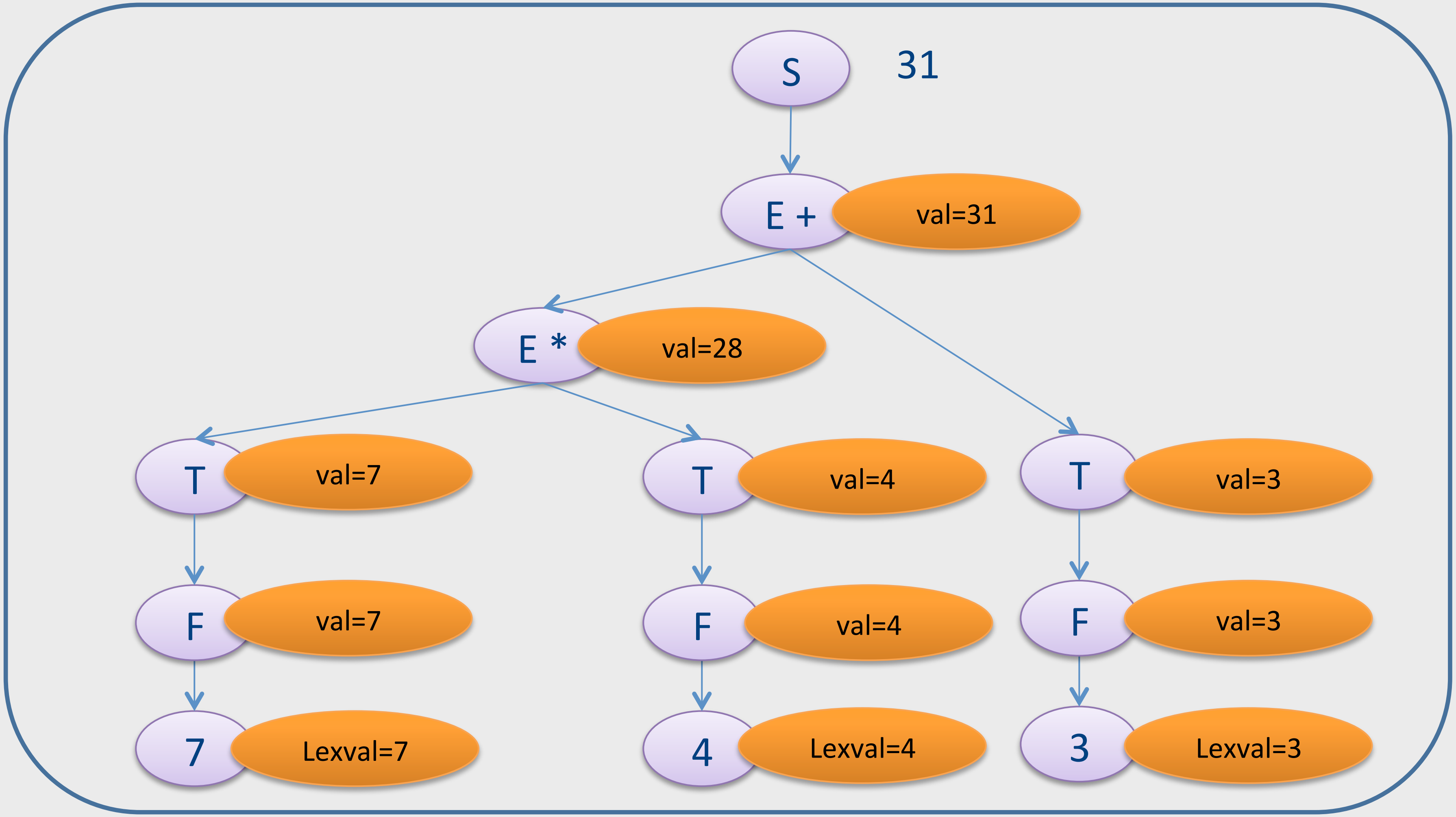
- Special class of attribute grammars
- Only uses synthesized attributes (S-attributed)
- No use of inherited attributes

- 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
$S \longrightarrow E$;	print(E.val)
$E \longrightarrow E1 + T$	E.val = E1.val + T.val
$E \longrightarrow T$	E.val = T.val
$T \longrightarrow T1 * F$	T.val = T1.val * F.val
$T \longrightarrow F$	T.val = F.val
$F \longrightarrow (E)$	F.val = E.val
$F \longrightarrow$ digit	F.val = digit.lexval

example



S
31
E +
val=31
E *
val=28
T
val=7
T
val=4
T
val=3
F
val=7
F
val=4
F
val=3
7
Lexval=7
4
Lexval=4
3
Lexval=3

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

Example: typesetting

- Each box is built from smaller boxes from which it gets the height and depth, and to which it sets the point size.
- pointsize (ps) – size of letters in a box. Subscript text has smaller point size of 0.7p.
- height (ht) – distance from top of the box to the baseline
- depth (dp) – distance from baseline to the bottom of the box.

Example: typesetting

production	semantic rules
S → B	B.ps = 10
B → B1 B2	B1.ps = B.ps B2.ps = B.ps B.ht = max(B1.ht,B2.ht) B.dp = max(B1.dp,B2.dp)
B → B1 sub B2	B1.ps = B.ps B2.ps = 0.7*B.ps B.ht = max(B1.ht,B2.ht – 0.25*B.ps) B.dp = max(B1.dp,B2.dp– 0.25*B.ps)
B → text	B.ht = getHt(B.ps,text.lexval) B.dp = getDp(B.ps,text.lexval)

Computing the attributes from left to right during a DFS traversal

```
procedure dfvisit (n: node);
begin
   for each child m of n, from left to right
     begin
         evaluate inherited attributes of m;
         dfvisit (m)
     end;
   evaluate synthesized attributes of n
end
```

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