

Semantic Analysis

The role of semantic analysis is to assign meaning

❏ "It smells fishy."

❏ Lexical analysis

- Tokenizes "It", "smells", "fishy", "."
- Determines noun, verb, adjective, punctuation token types

❏ Syntax analysis

- Parses the grammatical structure of the sentence

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❑ Syntax analysis

- Parses the grammatical structure of the sentence

❑ Semantic analysis

- Assigns meaning to the words "It", "smells", "fishy"
- Flags error if the sentence does not make sense

Semantic Analysis = Binding + Type Inference

- ❑ "I don't wanna eat that sushi."
 - "It smells fishy."
 - "It": the sushi
 - "smells": feels to my nose
 - "fishy": that the sushi has gone bad
- ❑ "The professor says that the exam is going to be easy."
 - "It smells fishy."
 - "It": the situation
 - "smells": feels to my sixth sense
 - "fishy": that it is highly suspicious

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"It smells fishy."
 - "It": the situation
 - "smells": feels to my sixth sense
 - "fishy": that it is highly suspicious
- ❑ Semantic analysis consists of two tasks
 - **Binding**: associating a pronoun to an object
 - **Type checking**: inferring meaning based on type of object

Semantic analysis cannot be done during parsing

❑ Context Free Grammars (CFGs) cannot recognize bindings

- Every use of a name needs to be bound to the declaration.
- Name can refer to a variable, function, class, ...
- Names are called **symbols** in semantic analysis

❑ To do bindings, a CFG must recognize this language:

$$\{\alpha c \alpha \mid \alpha \in (a|b)^*\}$$

The 1st α represents the declaration,

The 2nd α represents a use.

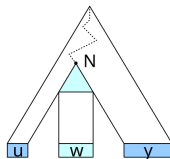
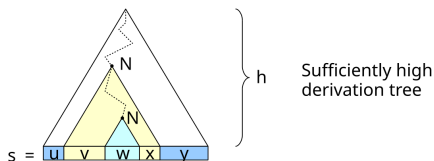
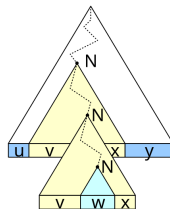
❑ Above language is a Context Sensitive Language

Why is $\{\alpha c \alpha \mid \alpha \in (a|b)^*\}$ not a CFG?

- ❑ We will base our proof on the **pumping lemma** for CFGs.
- ❑ **Pumping lemma:** a theorem about strings in a grammar
 - "lemma": a mathematical term for a theorem
 - "pumping": for a sufficiently long enough string, a substring exists within that string that can be "pumped" (repeated 0 or more times and still be in the language).
- ❑ For example, for the Regular Language $0(0|1)^*0$:
 - A string longer than 2 will look like 000, 010, 0100, ...
 - Let's take "010". Here, substring "1" can be pumped.
 - ("00", "010", "0110", "01110" are all in the language)
- ❑ Pumping Lemma applies to CFGs as well.

Pumping Lemma for CFGs

- For a sufficiently long string s derived from a CFG, s can be written as $s = uvwxy$ (u, v, w, x, y are substrings)
- Where v and x can be pumped and $|vx| \geq 1$.

Generating uv^kwx^ky Generating uv^kwx^ky

$\{\alpha c \alpha \mid \alpha \in (a|b)^*\}$ is not a CFG

□ Let's say $s = uvwxy$ is a sufficiently long string in language, where v and x can be pumped and $|vx| \geq 1$.

1. The substring $vw x$ must bisect s .

- If $vw x$ is contained in 1st α (or mostly contained), if we pump v and x 0 times, 1st α gets shorter than 2nd α .
- string is no longer in $\{\alpha c \alpha \mid \alpha \in (a|b)^*\}$. Contradiction.
- The same applies to when $vw x$ is contained in 2nd α .

2. Even when $vw x$ bisects s , pumping fails.

- Let string s' be the result of pumping v and x 0 times.
- Let's say $s' = \alpha_1 c \alpha_2$, where α_1 and α_2 are shortened versions of the 1st and 2nd α s.
- While $|\alpha_1| = |\alpha_2|$, there exist α_1 and α_2 such that $\alpha_1 \neq \alpha_2$.
- E.g. $s = abcab$, and $vw x = bca$ where $v = b$ and $x = a$. Then, α_1 becomes "a" and α_2 becomes "b". Contradiction.

Semantic analysis does binding and type checking

- ❑ Semantic analysis performs binding
 - Since CFGs cannot recognize bindings, as we just proved
 - Done by traversing parse tree produced by syntax analysis
 - Definitions are stored in data structure called **symbol table**
 - Uses are bound to entries in the symbol table
- ❑ Semantic analysis performs type checking
 - Infer what " $a + b$ " means:
 - If a and b are ints, integer add and return int
 - If a and b are floats, FP add and return float
 - If a and b are strings, concatenate and return string
 - Infer what " $a.foo()$ " means:
 - If object a is an instance of class A , call $A.foo()$
 - If object a is an instance of class B , call $B.foo()$
 - Infer what " $a[i][j]$ " means:
 - Offset from a calculated based on type and dimensions

Semantic analysis also performs semantic checks

- ❑ All symbol uses have a corresponding declaration;
- ❑ All operations are type legal;
- ❑ Inheritance relationships are correct;
- ❑ A class is defined only once;
- ❑ A method in a class is defined only once;
- ❑ ...

Symbol Binding

What is symbol binding?

“Matching symbol **declarations** with **uses**”

 If there are multiple declarations, which one is matched?

What is symbol binding?

“Matching symbol **declarations** with **uses**”

❑ If there are multiple declarations, which one is matched?

```
void foo()
{
    char x;
    ...
    {
        int x;
        ...
    }
    x = x + 1;
}
```

What is symbol binding?

“Matching symbol **declarations** with **uses**”

❑ If there are multiple declarations, which one is matched?

```
void foo()
{
    char x;
    ...
    {
        int x; ?
    }
    x = x + 1;
}
```

Scope

- ❑ **Binding**: the association of a use of a symbol to the declaration of that symbol
 - Which variable (or function) an identifier is referring to
- ❑ **Scope**: section of program where a declaration is valid
 - Uses in the scope of declaration are bound to it
- ❑ Some implications of scopes
 - A symbol may have different bindings in different scopes
 - Scopes for the same symbol never overlap
 - there is always exactly one binding per symbol use
- ❑ Two types: static scope and dynamic scope

Static Scope

- ❑ Static scope depends on the program text, not run-time behavior (also known as lexical scoping)
 - C/C++, Java, Objective-C
- ❑ Rule: Refer to the closest enclosing declaration

```
void foo()  
{  
    char x;  
  
    ...  
    {  
        int x;  
  
        ...  
    }  
    x = x + 1;  
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```

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```

Dynamic Scope

- Dynamic scoping depends on bindings formed during the execution of the program
 - LISP, Scheme, Perl
- Rule: Refer to the closest binding in the current execution

```
void foo()  
{  
  (1) char x;  
  (2) if (...) {  
    (3)   int x;  
    (4)   ...  
  }  
  (5) x = x + 1;  
}
```

Dynamic Scope

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void foo()  
{  
  (1) char x;  
  (2) if (...) {  
    (3)   int x;  
    (4)   ...  
  }  
  (5) x = x + 1;  
}
```

- Which x's declaration is the closest?
 - Execution (a): ...**(1)**...(2)...(5)
 - Execution (b): ...(1)...(2)...**(3)**...(4)...(5)

Static vs. Dynamic Scoping

- ❑ Most languages that started with dynamic scoping (LISP, Scheme, Perl) added static scoping afterwards
- ❑ Why?
 - It is easier for human beings to understand
 - Bindings visible in code without tracing execution
 - It is easier for compilers to understand
 - Compiler can determine bindings at compile time
 - Compiler can translate identifier to a single memory location
 - Results in generation of efficient code
 - With dynamic scoping...
 - There may be multiple possible bindings for a variable
 - Impossible to determine bindings at compile time
 - All bindings have to be done at execution time

Symbol Table

Symbol Table

- ❑ **Symbol Table:** A compiler data structure that tracks information about all identifiers (symbols) in a program
 - Maps symbol uses to declarations given a scope
 - Needs to provide bindings according to the current scope

- ❑ Usually discarded after generating the binary code
 - All symbols are mapped to memory locations already
 - For debugging, symbols may be included in binary
 - To map memory locations back to symbols for debuggers
 - For GCC or Clang, add “-g” flag to include symbol tables

Maintaining Symbol Table

Basic idea:

```
int x; ... void foo() { int x; ... x=x+1; } ... x=x+1 ...
```

- In *foo*, add *x* to table, overriding any previous declarations
- After *foo*, remove *x* and restore old declaration if any

Operations

`enter_scope()` start a new nested scope

`exit_scope()` exit current scope

`find_symbol(x)` find declaration of *x*

`add_symbol(x)` add declaration of *x* to symbol table

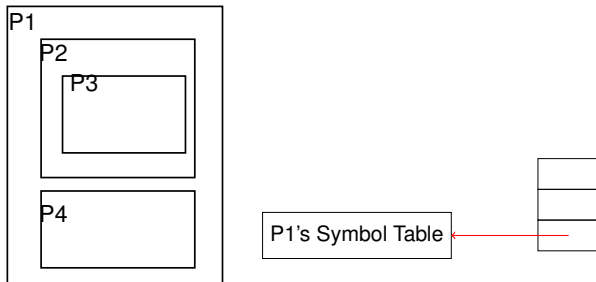
Adding Scope Information to the Symbol Table

- ❏ To handle multiple scopes in a program,
 - (Conceptually) need an individual table for each scope
 - Symbols added to the table may not be deleted just because you exited a scope

```
class X { ... void f1() {...} ... }  
class Y { ... void f2() {...} ... }  
X v;  
call v.f1();
```

- Without deleting symbols, how are scoping rules enforced?
 - ☞ Keep a list of all scopes in the entire program
 - ☞ Keep a stack of active scopes at a given point

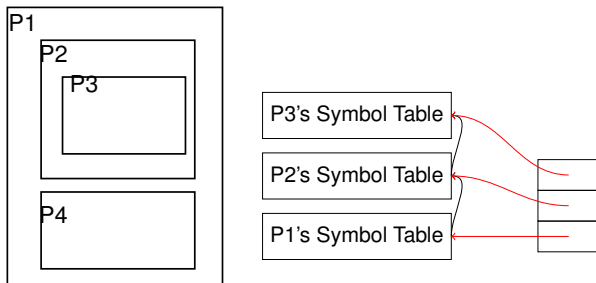
Symbol Table with Multiple Scopes



For nested scopes,

- Search from top of the active symbol table stack
- Remove pointer to symbol table when exiting its scope

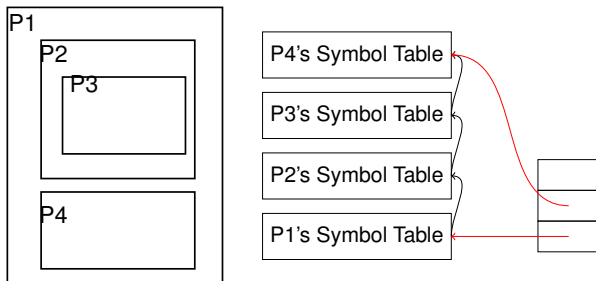
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What Information is Stored in the Symbol Table

Entry in Symbol Table:

string	kind	attributes
--------	------	------------

- String — the name of identifier
- Kind — variable, parameter, function, class, ...

Attributes vary with the kind of symbol

- variable → type, address in memory
- function → return type, parameter types, address

Vary with the language

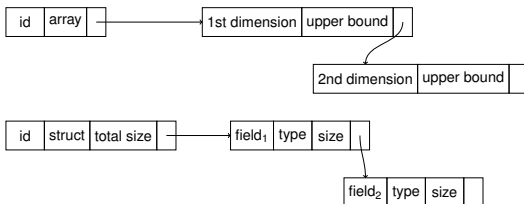
- Fortran's array → type, dimension, dimension size
`real A(5) /* dimension required for static allocation */`
- C's array → type, dimension, optional dimension size
`int A[5]; /* statically sized array */`
`int A[]; /* for dynamic allocation of array */`

Symbol Table Attribute List

- Type information might be arbitrarily complicated

➤ In C: struct {
 int a[10];
 char b;
 real c;
 }

- Store all relevant attributes in an attribute list

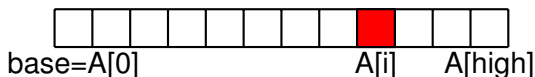


Example application of Type to an operator: Array index operator


Addressing Array Elements

```
int A[0..high];
```

```
A[i] ++;
```



- width — width of element type
- base — address of the first
- high — upper bound of subscript

 Addressing an array element:

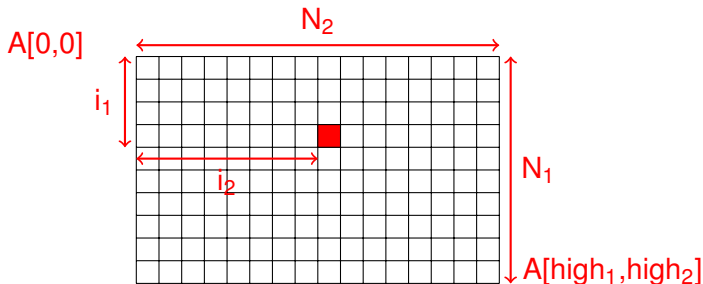
```
address(A[i])  
= base + i * width
```


Multi-dimensional Arrays

- Layout n-dimension items in 1-dimension memory

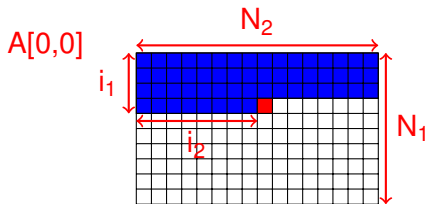
```
int A[N1][N2]; /* int A[0..high1][0..high2]; */
```

```
A[i1][i2] ++;
```



Row Major

Row major — store row by row

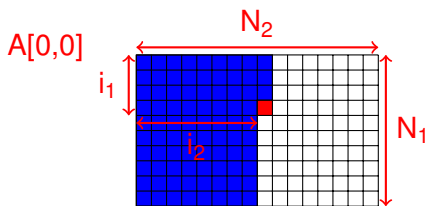


□ Offset includes all the “blue” items before $A[i_1, i_2]$

$$\begin{aligned} &\text{address}(A[i_1, i_2]) \\ &= \text{base} + (i_1 * N_2 + i_2) * \text{width} \end{aligned}$$

Column Major

Column major — store column by column



□ Offset includes all the “blue” items before $A[i_1, i_2]$

$$\begin{aligned} \text{address}(A[i_1, i_2]) \\ = \text{base} + (i_2 * N_1 + i_1) * \text{width} \end{aligned}$$

Generalized Row/Column Major

□ Calculating A_k = offset of $A[i_1, i_2, \dots, i_k]$ from base address:

□ Row major

1-dimension: $A_1 = i_1 * \text{width}$

2-dimension: $A_2 = (i_1 * N_2 + i_2) * \text{width} = A_1 * N_2 + i_2 * \text{width}$

3-dimension: $A_3 = (i_1 * N_2 * N_3 + i_2 * N_3 + i_3) * \text{width} = A_2 * N_3 + i_3 * \text{width}$

...

k-dimension: $A_k = A_{k-1} * N_k + i_k * \text{width}$

□ Column major

1-dimension: $A_1 = i_1 * \text{width}$

2-dimension: $A_2 = (i_2 * N_1 + i_1) * \text{width} = i_2 * N_1 * \text{width} + A_1$

3-dimension: $A_3 = ((i_3 * N_2 + i_2) * N_1 + i_1) * \text{width} = i_3 * N_2 * N_1 * \text{width} + A_2$

...

k-dimension: $A_k = i_k * N_{k-1} * N_{k-2} * \dots * N_1 * \text{width} + A_{k-1}$

C's implementation

❏ C uses row major

```
int fun1(int p[ ][100])  
{  
  ...  
  int a[100][100];  
  a[i1][i2] = p[i1][i2] + 1;  
}
```

Why is p[][100] allowed?

Why is a[][100] not allowed?

C's implementation

❏ C uses row major

```
int fun1(int p[ ][100])  
{  
  ...  
  int a[100][100];  
  a[i1][i2] = p[i1][i2] + 1;  
}
```

Why is `p[][100]` allowed?

- The info is enough to compute `p[i1][i2]`'s address
- $A_2 = (i_1 * N_2 + i_2) * \text{width}$ (N_1 is not required)

Why is `a[][100]` not allowed?

- The info is not enough to allocate space for the array

Type Checking

What, Why and When

❑ What is a type?

Type = a set of values + a set of operations on these values

❑ What is type checking?

Verifying and enforcing type consistency

- Only legal values are assigned to a type
- Only legal operations are performed on a type

❑ Why is compile-time type checking desirable?

- Type errors easier to debug than malfunctioning programs
- Dynamic type checking when static checking infeasible
 - E.g. Java null checks and array bounds checks
 - E.g. C++/Java downcasting to a subclass

Static vs. Dynamic Typing

❑ Statically typed: C/C++, Java

👉 Our discussion

- Types are explicitly declared or can be inferred from code
- E.g. `int x; /* type of x is int */`
- Efficient code since runtime type checks are not needed

❑ Dynamically typed: Python, JavaScript, PHP

- Type is a runtime property decided only during execution
- E.g. `var x; /* type of x is undecided */`
- Type of x changes depending on the type of value it holds
- More memory since every variable now needs a "type tag"
- Inefficient code due to runtime checks on type tags

Rules of Inference

□ What are *rules of inference*?

- Inference rules have the form
if **Precondition** is true, then **Conclusion** is true
- Below concise notation used to express above statement

Precondition
Conclusion

- In the context of type checking:
if expressions E1, E2 have certain types (Precondition),
expression E3 is legal and has a certain type (Conclusion)

□ Type checking via inference

- Start from variable types and constant types
- Repeatedly apply rules until entire program is inferred legal

Notation for Inference Rules

- By tradition inference rules are written as

$$\frac{\text{Precondition}_1, \dots, \text{Precondition}_n}{\text{Conclusion}}$$

- The precondition/conclusion has the form “**e:T**”

- Meaning

- If **Precondition**₁ and ... and **Precondition**_n are true, then **Conclusion** is true.
- “**e:T**” indicates “**e is of type T**”
- Example: rule-of-inference for add operation

$$\frac{e_1: \text{int} \quad e_2: \text{int}}{e_1 + e_2: \text{int}}$$

Rule: If e_1, e_2 are ints then $e_1 + e_2$ is legal and is an int

Two Simple Rules

[Constant]

$$\frac{\text{**i is an integer**}}{\text{**i: int**}}$$

[Add operation]

$$\frac{\begin{array}{l} \text{**e}_1\text{: int} \\ \text{**e}_2\text{: int} \end{array}}{\text{**e}_1\text{+e}_2\text{:int}}}******$$

□ Example: given “10 is an integer” and “20 is an integer”, is the expression “10+20” legal? Then, what is the type?

$$\frac{\frac{\text{**10 is an integer**}}{\text{**10: int**}} \quad \frac{\text{**20 is an integer**}}{\text{**20: int**}}}{\text{**10+20:int**}}$$

□ This type of reasoning can be applied to the entire program

More Rules

[New]

new T: T

[Not]

e: Boolean
not e: Boolean

 However,

[Var?]

x is an identifier
x: ?

- the expression itself insufficient to determine type
- **solution:** provide context for this expression

Type Environment

- ❏ A *type environment* gives type info for free variables
 - A variable is *free* if not declared inside the expression
 - It is a function mapping **Symbols** to **Types**
 - Set of declarations active at the current scope
 - Conceptual representation of a symbol table

Type Environment Notation

Let \mathcal{O} be a function from **Symbols** to **Types**,
the sentence $\mathcal{O} \ e:T$

is read as “under the assumption of environment \mathcal{O} ,
expression e has type T ”

$$\frac{i \text{ is an intger}}{\mathcal{O} \ i: \text{int}}$$

$$\frac{\begin{array}{l} \mathcal{O} \ e1: \text{int} \\ \mathcal{O} \ e2: \text{int} \end{array}}{\mathcal{O} \ e1+e2: \text{int}}$$

$$\frac{\mathcal{O}(x): T}{\mathcal{O} \ x: T}$$

- “if i is an integer, expression i is an int in any environment”
- “if $e1$ and $e2$ are ints in \mathcal{O} , expression $e1+e2$ is int in \mathcal{O} ”
- “if variable x is mapped to int in \mathcal{O} , expression x is int in \mathcal{O} ”

Declaration Rule

[Declaration w/o initialization]

$$\frac{O[T_0/x] \ e_1 : T_1}{O \text{ let } x : T_0 \text{ in } e_1 : T_1}$$

$O[T_0/x]$ means, O is modified to return T_0 on argument x and behaves as O on all other arguments

$$O[T_0/x](x) = T_0$$

$$O[T_0/x](y) = O(y) \text{ when } x \neq y$$

- Translation: "If expression e_1 is type T_1 when x is mapped to type T_0 in the current environment, expression e_1 is type T_1 when x is declared to be T_0 in the current environment"

Declaration Rule with Initialization

[Declaration with initialization (initial try)]

$$\frac{\begin{array}{c} \mathbf{O} \ e_0 : T_0 \\ \mathbf{O}[T_0/x] \ e_1 : T_1 \end{array}}{\mathbf{O} \ \text{let } x : T_0 \leftarrow e_0 \text{ in } e_1 : T_1}$$

❏ The rule is too strict (i.e. correct but not complete)

Example

class C inherits P ...

let x:P \leftarrow new C in ...

☞ the above rule does not allow this code

Subtyping

□ Subtyping is a relation \leq on classes

- $X \leq X$
- if X inherits from Y , then $X \leq Y$
- if $X \leq Y$ and $Y \leq Z$, then $X \leq Z$

□ An improvement of our previous rule

[Declaration with initialization]

$$\frac{\begin{array}{c} O\ e_0: T \\ T \leq T_0 \\ O[T_0/x]\ e_1: T_1 \end{array}}{O\ \text{let } x: T_0 \leftarrow e_0\ \text{in } e_1: T_1}$$

- Both versions of declaration rules are correct
- The improved version checks more programs

Assignment

- ❏ A correct but too strict rule

[Assignment]

$O(id) = T_0$

$O e_1: T_1$

$T_1 \leq T_0$

$O id \leftarrow e_1: T_0$

- The rule does not allow the below code
- ```
class C inherits P { only_in_C() { ... } }
x ← y ← new C
x.only_in_C()
```

# Assignment

 An improved rule

[Assignment]

$O(id) = T_0$

$O\ e_1: T_1$

$T_1 \leq T_0$

---

$O\ id \leftarrow e_1: T_1$

- The rule now does allow the below code
- ```
class C inherits P { only_in_C() { ... } }
x ← y ← new C
x.only_in_C()
```

If-then-else

Consider

if e_0 then e_1 else e_2

- The result can be either e_1 or e_2
 - The type is either e_1 's type or e_2 's type
- The best that we can do (statically) is the super type larger than e_1 's type and e_2 's type

Least upper bound (LUB)

- $Z = \text{lub}(X, Y)$ — Z is defined as the least upper bound of X and Y iff
- $X \leq Z \wedge Y \leq Z$; Z is an upper bound
 - $X \leq W \wedge Y \leq W \implies Z \leq W$; Z is least among all upper bounds

If-then-else, case

[If-then-else]

$$\frac{\begin{array}{l} \mathbf{O\ } e_0 : \mathbf{Bool} \\ \mathbf{O\ } e_1 : T_1 \\ \mathbf{O\ } e_2 : T_2 \end{array}}{\mathbf{O\ if\ } e_0 \mathbf{\ then\ } e_1 \mathbf{\ else\ } e_2 \mathbf{\ fi:\ lub}(T_1, T_2)}$$

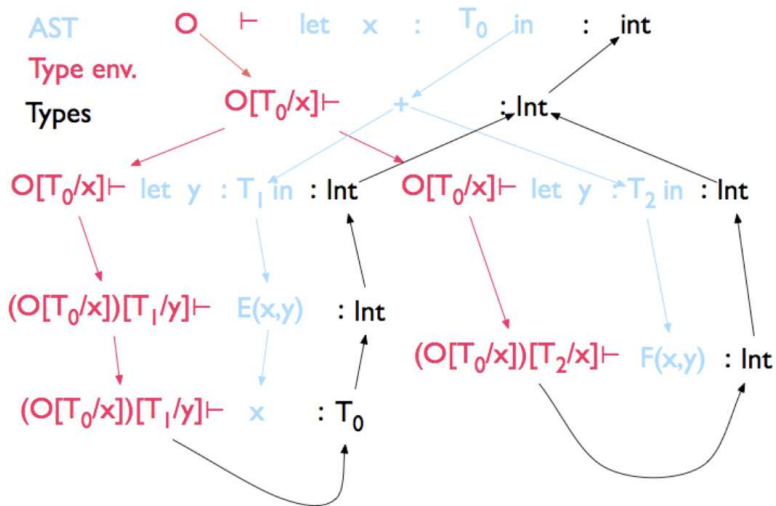
□ The rule allows the below code

let x:float, y:int, z:float in

x \leftarrow if (...) then y else z

/* Assuming $\text{lub}(\text{int}, \text{float}) = \text{float}$ */

Implementing Type Checking on AST



Error Recovery

❏ Just like other errors, we should recover from type errors

➤ Too many errors?

let y: int \leftarrow x+2 in y+3

- if x is undefined — reporting an error “x type undefined”
- x+2 is undefined — reporting an error “x+2 type undefined”
- ...

❏ Introducing **no-type** for ill-typed expressions

- It is compatible with all types
- Report the place where **no-type** is generated
 - Reduce the number of error messages

Wrong Declaration Rule (case 1)

❏ Consider a hypothetical let rule

[Wrong Declaration with initialization (case 1)]

$$\frac{\begin{array}{c} \mathbf{O} \ e_0: T \\ T \leq T_0 \\ \mathbf{O} \ e_1: T_1 \end{array}}{\mathbf{O} \ \text{let } x: T_0 \leftarrow e_0 \text{ in } e_1: T_1}$$

- How is it different from the the correct rule?
- The following program does not pass check
`let x: Int ← 0 in x+1`

Wrong Declaration Rule (case 2)

❏ Consider a hypothetical let rule

[Wrong Declaration with initialization (case 2)]

$$\frac{\begin{array}{c} O\ e_0: T \\ T_0 \leq T \\ O[T_0/x]\ e_1: T_1 \end{array}}{O\ \text{let } x: T_0 \leftarrow e_0 \text{ in } e_1: T_1}$$

- How is it different from the the correct rule?
- The following bad program passes the check
`let x: B ← new A in x.b()`

Wrong Declaration Rule (case 3)

❏ Consider a hypothetical let rule

[Wrong Declaration with initialization (case 3)]

$$\frac{\begin{array}{c} \mathbf{O} \ e_0: T \\ T_0 \leq T \\ \mathbf{O}[T/x] \ e_1: T_1 \end{array}}{\mathbf{O} \ \text{let } x: T_0 \leftarrow e_0 \text{ in } e_1: T_1}$$

- How is it different from the the correct rule?
- The following bad program passes the check

let x: A \leftarrow new B in {... x \leftarrow new A; x.a(); }

Discussion

- ❑ Type rules have to be very carefully constructed
- ❑ Virtually any change in a rule either
 - makes the type system unsound
(bad programs are accepted as well typed)
 - or, makes the type system less usable
(good programs are rejected)
- ❑ But some good programs will be rejected anyway
 - what is a “good” program ?

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- ❑ But some good programs will be rejected anyway
 - what is a “good” program ?
 - Good program: A program where all operations performed on all values are type consistent **at runtime**
 - Impossible to express all runtime behavior in a type system
 - E.g. Type of if-then-else is LUB of two types, a conservative estimate of runtime behavior

Designing a Good Type Checking System

- ❑ Type system has two conflicting design goals
 - Give flexibility to the programmer (so that she can write a “good” program within the boundaries of the type system)
 - Prevent type-checked programs from “going wrong”
- ❑ Should allow maximum flexibility while guaranteeing safety
 - An example

```
class Count {  
    int i = 0;  
    Count inc() { i=i+1; return this; }  
}  
class Stock inherits Count { ... }  
class Main {  
    Stock a ← (new Stock).inc();  
}
```

What Went Wrong?

- ❏ What is `(new Stock).inc()`'s type?
 - Dynamic type — `Stock`
 - Static type — `Count`
 - The type checker “looses” the type information
 - This makes inheriting `inc()` useless
 - Do we really want to redefine `inc()` for each subclass returning the correct type?
- ❏ `SELF_TYPE` to the rescue

SELF_TYPE to the Rescue

❏ What is SELF_TYPE?

- `inc()` returns “self” instead of “Count” type
- Self could be Count or any subclass of Count, depending on reference type

❏ SELF_TYPE is a static type

- Type violations can still be detected at compile time
- Expresses runtime behavior accurately w/o undue burden to the programmer

❏ In practice

- C++: made possible by language extension using templates
- Java: not allowed because there are no templates

Can Static Type Checking ever be Perfect?

- ❑ Many examples where correct programs are disallowed (besides SELF_TYPE)
 - Why C++ programmers are still forced to downcast (Type of values at runtime are known by programmer but no way to express it in type system)
 - Fundamentally undecidable whether type system is adhered to at runtime
- ❑ Solution?
 - Some argue for dynamic type checking instead
 - Philosophy: Maximum expressivity for the programmer
 - Good for scripting languages where expressivity is king
 - Others argue for more expressive static checking rules
 - Philosophy: Too much expressivity is not good for you
 - Good for mission critical code that should never fail
 - Good for performance critical code

Syntax Directed Translation

What is Syntax Directed Translation?

- ❑ To drive **semantic analysis tasks** based on the language's **syntactic structure**

- ❑ What is meant by semantic analysis tasks?
 - Generate AST (abstract syntax tree)
 - Check type errors
 - Generate intermediate representation (IR)
- ❑ What is meant by syntactic structure?
 - Structure of program given by context free grammar (CFG)
 - Structure of the parse tree generated by the parser

How is Syntax Directed Translation Performed?

□ How?

- Attach **attributes** to grammar symbols/parse tree
- Evaluate attribute values using **semantic actions**

□ We already did some of this in Project 2:

- Attached attributes to grammar symbols
 - **tptr** — “tree pointer” of a non-terminal symbol
By the time **program.tptr** is evaluated, the parse tree is built
- Evaluated attributes using semantic rules (actions)
 - { ... \$\$=makeTree(ProgramOp, leftChild, rightChild); ... }

Attributes?

- ❑ Attributes can represent anything depending on task
 - A string
 - A type
 - A number
 - A memory location
- ❑ An **attribute grammar** is a grammar augmented by associating attributes with each grammar symbol that describes its properties

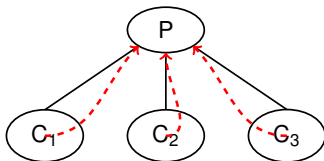
Two Types of Attributes

- ❑ **Synthesized attributes:** attributes are computed from attributes of children nodes

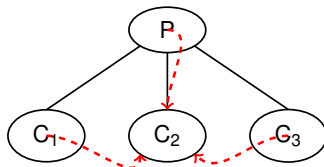
➤ $P.\text{synthesized_attr} = f(C_1.\text{attr}, C_2.\text{attr}, C_3.\text{attr})$

- ❑ **Inherited attributes:** attributes are computed from attributes of sibling and parent nodes

➤ $C_3.\text{inherited_attr} = f(P_1.\text{attr}, C_1.\text{attr}, C_3.\text{attr})$



Synthesized attribute



Inherited attribute

Synthesized Attribute Example

Example

- Each non-terminal symbol is associated with **val** attribute
- Each grammar rule is associated with a **semantic action**

$L \rightarrow E$	{ print(E.val) }
$E \rightarrow E_1 + T$	{ E.val = E ₁ .val + T.val }
$E \rightarrow T$	{ E.val = T.val }
$T \rightarrow T_1 + F$	{ T.val = T ₁ .val + F.val }
$T \rightarrow F$	{ T.val = F.val }
$F \rightarrow (E)$	{ F.val = E.val }
$F \rightarrow \text{digit}$	{ F.val = digit.lexval }

Inherited Attribute Example

Example:

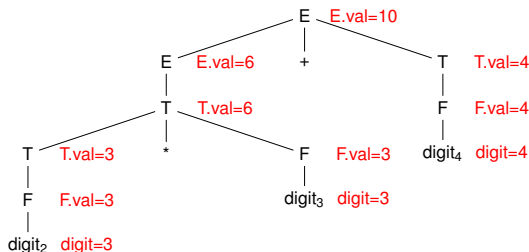
- T — synthesized attribute “type”
- L — has inherited attribute “in”

```
D → T L    { L.in = T.type }  
T → int    { T.type = integer }  
T → real   { T.type = real }  
L → L1 , id { L1.in = L.in, addtype (id.entry, L.in) }  
L → id     { addtype(id.entry, L.in) }
```

- We can use *inherited attributes* to track **type** information
- We can use *inherited attributes* to track whether an identifier appear on the left or right side of an assignment operator “:=” (e.g. `a := a + 1`)

Attribute Parse Tree

- Parse tree showing values of attributes
 - Parse tree annotated or decorated with attributes
 - Attributes computed at each node
- Properties of attribute parse tree:
 - Terminal symbols — have synthesized attributes only, which are usually provided by the lexical analyzer
 - Start symbol — does not have any inherited attributes



Two Aspects to Syntax Directed Translation

□ Syntax Directed Definitions (SDD)

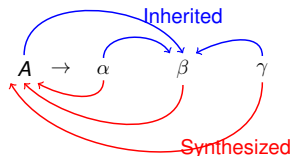
- Set of **semantic rules** attached to each production
- Semantic rules define values for attributes
- Specification rather than implementation

□ Syntax Directed Translation Scheme (SDTS)

- Semantic actions are **implementations of semantic rules**
- Grammar with **semantic actions** embedded within RHS of productions (can be anywhere)
- Semantic actions are fragments of code executed “at that point” in the RHS
 - Top-down: Right after previous symbol has been consumed
 - Bottom-up: Right after previous symbol has been pushed to the stack (when the 'dot' reaches the action)

Syntax Directed Definition (SDD)

Attribute grammar



SDD has rule of the form for each CFG production

$$b = f(c_1, c_2, \dots, c_n)$$

either

1. If b is a synthesized attribute of A , c_i ($1 \leq i \leq n$) are attributes of grammar symbols of its Right Hand Side (RHS); or
2. If b is an inherited attribute of one of the symbols of RHS, c_i 's are attribute of A and/or other symbols on the RHS

Syntax Directed Translation Scheme (SDTS)

$$\begin{aligned}E &\rightarrow T \ R \\R &\rightarrow + \ T \ R \\R &\rightarrow - \ T \ R \\R &\rightarrow \varepsilon \\T &\rightarrow (\ E \) \\T &\rightarrow \text{num}\end{aligned}$$

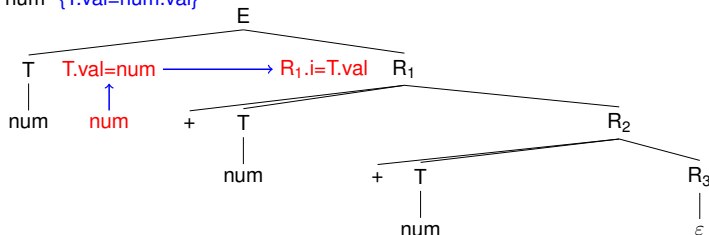
 Both inherited and synthesized attributes are used

- T — synthesized attribute T.val
- R — inherited attribute R.i
synthesized attribute R.s
- E — synthesized attribute E.val

Syntax Directed Translation Scheme (SDTS)

Evaluating attributes using SDTS

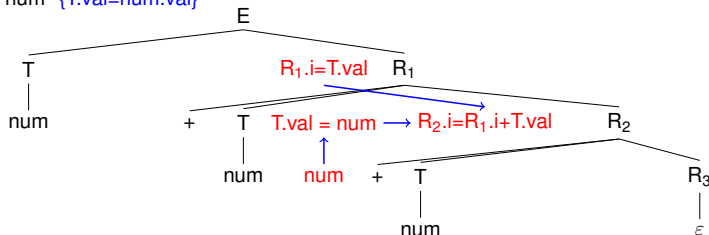
$E \rightarrow T \quad \{R.i = T.val\} \quad R \quad \{E.val = R.s\}$
 $R \rightarrow + \quad T \quad \{R_1.i = R.i + T.val\} \quad R_1 \quad \{R.s = R_1.s\}$
 $R \rightarrow - \quad T \quad \{R_1.i = R.i - T.val\} \quad R_1 \quad \{R.s = R_1.s\}$
 $R \rightarrow \varepsilon \quad \{R.s = R.i\}$
 $T \rightarrow (\quad E \quad \{T.val = E.val\}$
 $T \rightarrow \text{num} \quad \{T.val = \text{num.val}\}$



Syntax Directed Translation Scheme (SDTS)

□ Evaluating attributes using SDTS

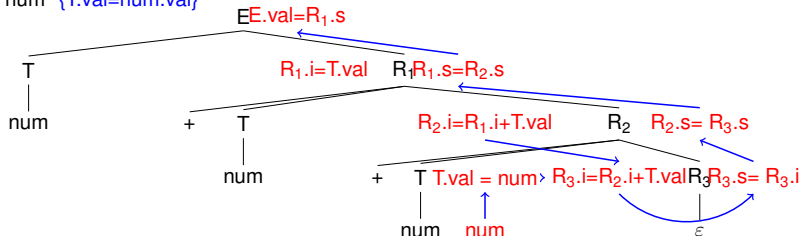
$E \rightarrow T \quad \{R.i=T.val\} \quad R \quad \{E.val=R.s\}$
 $R \rightarrow + \quad T \quad \{R_1.i=R.i+T.val\} \quad R_1 \quad \{R.s=R_1.s\}$
 $R \rightarrow - \quad T \quad \{R_1.i=R.i-T.val\} \quad R_1 \quad \{R.s=R_1.s\}$
 $R \rightarrow \varepsilon \quad \{R.s=R.i\}$
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 $T \rightarrow \text{num} \quad \{T.val=\text{num.val}\}$



Syntax Directed Translation Scheme (SDTS)

Evaluating attributes using SDTS

$E \rightarrow T \quad \{R.i = T.val\} \quad R \quad \{E.val = R.s\}$
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 $T \rightarrow \text{num} \quad \{T.val = \text{num.val}\}$

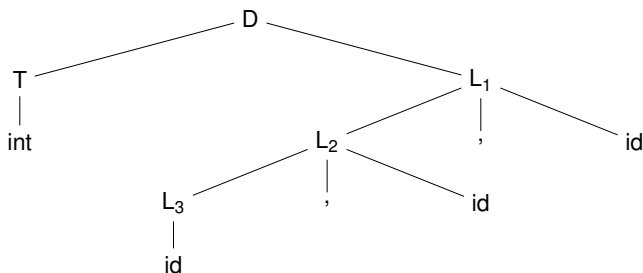


SDD Implementation using Parse Trees

- ❑ Alternative to using Syntax Directed Translation Scheme
- ❑ Goal: create an **annotated parse tree** from the given parse tree
 - Annotated parse tree: tree annotated with attribute values
 - Traverse in a certain order and evaluate semantic rules at each node
 - Traversal order can be arbitrary as long as it adheres to dependency relationships

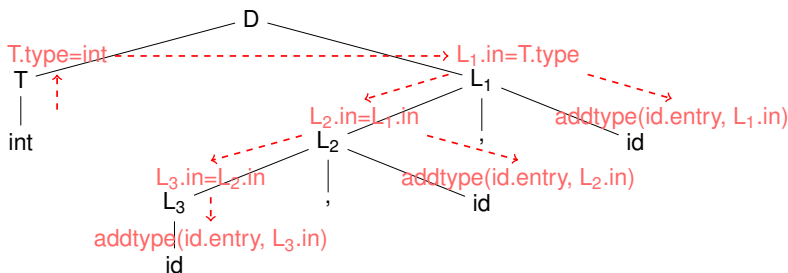
Dependency Graph

- Directed graph where edges are dependency relationships between attributes
 - Needs to be acyclic such that there exists a traversal order for evaluation
 - i.e. all necessary information must be ready when evaluating an attribute at a node



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SDD Implementation using SDTS

- ❑ Tree-based evaluation works for all SDDs unless there is a dependency cycle
 - But involves more work since parse tree must be built initially
 - And the question still remains, how do you build the parse tree itself?
- ❑ Is it possible to perform evaluation **while parsing**?
 - Embed semantic actions in grammar using SDTS
 - What are some potential problems?
 - Parser may not have even "seen" some nodes yet
 - Some dependencies may not exist at time of evaluation
 - Different parsing schemes see nodes in different orders
 - Top-down parsing — LL(k) parsing
 - Bottom-up parsing — LR(k) parsing
- ❑ For certain classes of SDDs, using SDTS is feasible
 - if dependencies of SDD are amenable to parse order
 - In other words, an L-Attributed Grammar

Left-Attributed Grammar

□ A syntax directed translation is L-attributed if each of its attributes is

either

➤ a synthesized attribute of A in $A \rightarrow X_1 \dots X_n$,

or

➤ an inherited attribute of X_j in $A \rightarrow X_1 \dots X_n$ that

- depends on attributes of symbols to its left i.e. $X_1 \dots X_{j-1}$
- and/or depends on inherited attributes of A

Left-Attributed Grammar

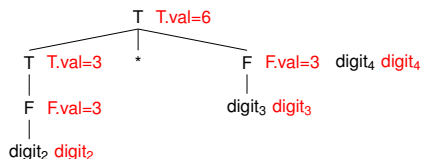
- ❑ An L-Attributed grammar
 - may have synthesized attributes
 - may have inherited attributes but only from left sibling attributes or inherited attributes of the parent
- ❑ Evaluation order
 - Left-to-right depth-first traversal of the parse tree
 - Order for both top-down and bottom-up parsers
 - Evaluate inherited attributes while going down the tree
 - Evaluate synthesized attributes while going up the tree
- ❑ Can be evaluated using SDTS w/o parse tree

Syntax Directed Translation Scheme Implementation

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is natural and easy to evaluate synthesized attributes



parsing stack:

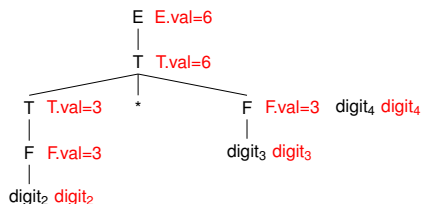
S?	T	T.val=6
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

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parsing stack:

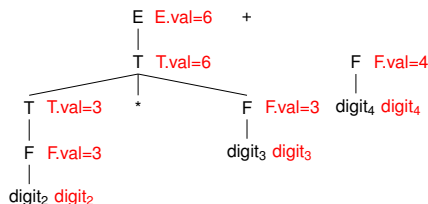
S?	E	E.val=6
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is natural and easy to evaluate synthesized attributes



parsing stack:

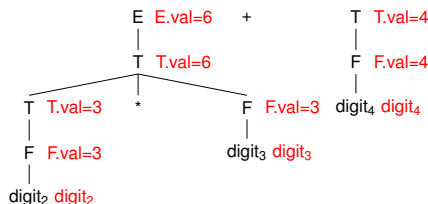
S?	F	F.val=4
S?	+	-
S?	E	E.val=6
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is natural and easy to evaluate synthesized attributes



parsing stack:

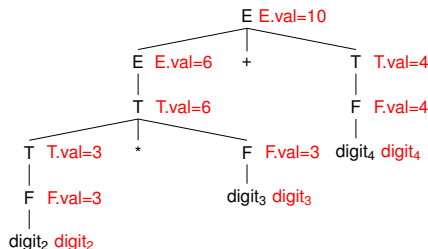
S?	T	T.val=4
S?	+	-
S?	E	E.val=6
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is natural and easy to evaluate synthesized attributes



parsing stack:

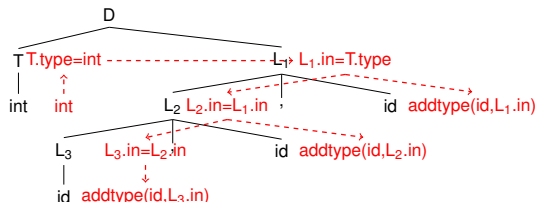
S?	E	E.val=10
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is **not natural** to evaluate inherited attributes



parsing stack:

$S_?$	$\$$	$-$

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is **not natural** to evaluate inherited attributes

```

int          ,          id
          ,          id
id
  
```

parsing stack:

S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

it is **not natural** to evaluate inherited attributes

T **T.type=int**
|
int **int**

, id

, id

id

parsing stack:

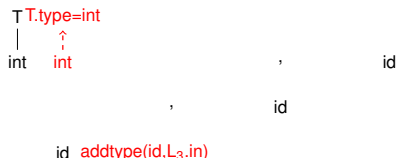
S?	T	T.type=int
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

it is **not natural** to evaluate inherited attributes



parsing stack:

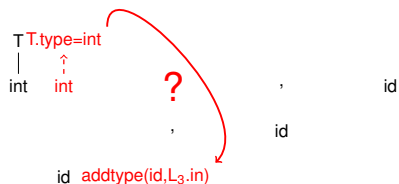
S?	id	id.type=L ₃ .in
S?	T	T.type=int
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is **not natural** to evaluate inherited attributes



parsing stack:

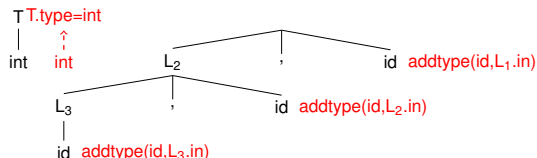
$S_?$	id	$id.type=L_3.in$
$S_?$	T	$T.type=int$
$S_?$	$\$$	$-$

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is **not natural** to evaluate inherited attributes



parsing stack:

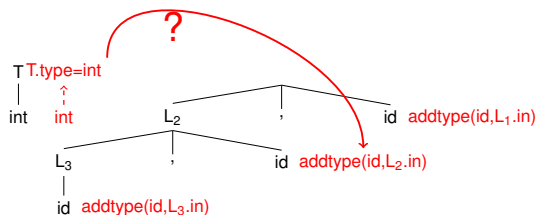
S?	id	id.type=L ₃ .in
S?	T	T.type=int
S?	\$	-

(state) (symbol) (attribute)

Translation Scheme for Bottom-Up Parsing

When using LR parsing (bottom-up parsing),

□ it is **not natural** to evaluate inherited attributes



parsing stack:

S?	id	id.type=L ₃ .in
S?	T	T.type=int
S?	\$	-

(state) (symbol) (attribute)

Evaluating Inherited Attributes using LR

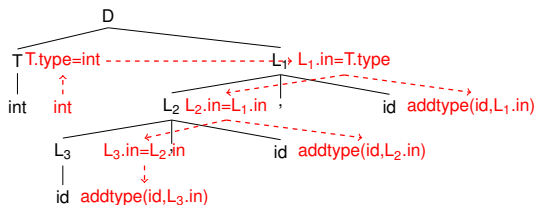
- ❑ Recall
- ❑ Only applies to L-Attributed grammars
 - 👉 What is L-attributed grammar?
- ❑ **Claim:** the information is in the stack, we just do not know the exact location
- ❑ **Solution:** let us hack the stack to find the location

$$D \rightarrow T \quad L$$

$$T \rightarrow \text{int} \quad \{\text{stack}[\text{top}] = \text{integer}\}$$

$$T \rightarrow \text{real} \quad \{\text{stack}[\text{top}] = \text{real}\}$$

$$L \rightarrow L \quad , \quad \text{id} \quad \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-3])\}$$

$$L \rightarrow \text{id} \quad \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$


parsing stack:

$S_?$	$\$$	-

(state) (symbol) (attribute)

$$D \rightarrow T \mid L$$

$$T \rightarrow \text{int} \quad \{\text{stack}[\text{top}] = \text{integer}\}$$

$$T \rightarrow \text{real} \quad \{\text{stack}[\text{top}] = \text{real}\}$$

$$L \rightarrow L \mid \text{id} \quad \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-3])\}$$

$$L \rightarrow \text{id} \quad \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$

int

,

id

,

id

id

parsing stack:

S ₇	\$	-

(state) (symbol) (attribute)

$$D \rightarrow T \ L$$

$$T \rightarrow \text{int} \ \{\text{stack}[\text{top}]=\text{integer}\}$$

$$T \rightarrow \text{real} \ \{\text{stack}[\text{top}]=\text{real}\}$$

$$L \rightarrow L \ , \ \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-3])\}$$

$$L \rightarrow \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$

$$T \text{ T.type=int}$$

$$\begin{array}{c} | \\ \text{int} \end{array} \quad \begin{array}{c} \uparrow \\ \text{int} \end{array}$$

,

id

,

id

id

parsing stack:

S?	T	T.type=int
S?	\$	-

(state) (symbol) (attribute)

$$D \rightarrow T \ L$$

$$T \rightarrow \text{int} \ \{\text{stack}[\text{top}]=\text{integer}\}$$

$$T \rightarrow \text{real} \ \{\text{stack}[\text{top}]=\text{real}\}$$

$$L \rightarrow L \ , \ \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-3])\}$$

$$L \rightarrow \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$

T $T.\text{type}=\text{int}$
 \mid \uparrow
 int int

, id

, id

id $\text{addtype}(\text{id}, L_3.\text{in})$

parsing stack:

$S_?$	id	$\text{id.type}=\text{stack}[\text{top}-1]$
$S_?$	T	$T.\text{type}=\text{int}$
$S_?$	\$	-

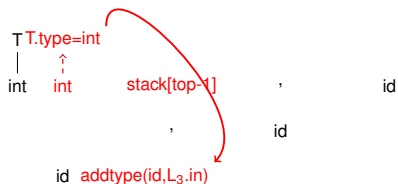
(state) (symbol) (attribute)

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$$L \rightarrow \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$


parsing stack:

$S_?$	id	id.type=stack[top-1]
$S_?$	T	T.type=int
$S_?$	\$	-

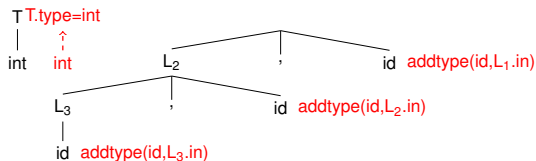
(state) (symbol) (attribute)

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$$L \rightarrow \text{id} \quad \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$


parsing stack:

S ₇	id	id.type=stack[top-3]
S ₇	,	
S ₇	L ₃	L ₃ .in=int
S ₇	T	T.type=int
S ₇	\$	-

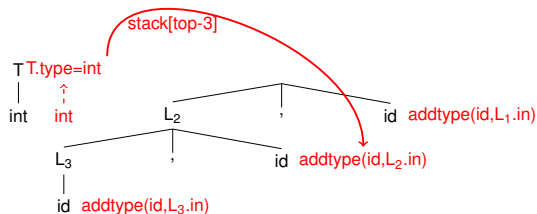
(state) (symbol) (attribute)

$$D \rightarrow T \ L$$

$$T \rightarrow \text{int} \ \{\text{stack}[\text{top}] = \text{integer}\}$$

$$T \rightarrow \text{real} \ \{\text{stack}[\text{top}] = \text{real}\}$$

$$L \rightarrow L \ , \ \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-3])\}$$

$$L \rightarrow \text{id} \ \{\text{addtype}(\text{stack}[\text{top}], \text{stack}[\text{top}-1])\}$$


parsing stack:

S _?	id	id.type=stack[top-3]
S _?	,	
S _?	L ₃	L ₃ .in=int
S _?	T	T.type=int
S _?	\$	-

(state) (symbol) (attribute)

Marker

- Given the following SDD, where $|\alpha| \neq |\beta|$

$$A \rightarrow X \alpha Y \mid X \beta Y$$

$$Y \rightarrow \gamma \{ \dots = f(X.s) \}$$
- Problem: cannot generate stack location for $X.s$ since X is at different relative stack locations from Y
- Solution: introduce *markers* M_1 and M_2 that are at the same relative stack locations from Y

$$A \rightarrow X \alpha M_1 Y \mid X \beta M_2 Y$$

$$Y \rightarrow \gamma \{ \dots = f(M_{12}.s) \}$$

$$M_1 \rightarrow \varepsilon \{ M_1.s = X.s \}$$

$$M_2 \rightarrow \varepsilon \{ M_2.s = X.s \}$$

(M_{12} = the stack location of M_1 or M_2 , which are identical)
- A marker intuitively marks a stack location that is equidistant from the reduced non-terminal

Example

How to add the marker ?

Example 1:

$$\begin{aligned} S &\rightarrow a A \{ C.i = A.s \} C \\ S &\rightarrow b A B \{ C.i = A.s \} C \\ C &\rightarrow c \{ C.s = f(C.i) \} \end{aligned}$$

Solution:

$$\begin{aligned} S &\rightarrow a A \{ C.i = A.s \} C \\ S &\rightarrow b A B \{ M.i=A.s \} M \{ C.i = M.s \} C \\ C &\rightarrow c \{ C.s = f(C.i) \} \\ M &\rightarrow \varepsilon \{ M.s = M.i \} \end{aligned}$$

That is:

$$\begin{aligned} S &\rightarrow a A C \\ S &\rightarrow b A B M C \\ C &\rightarrow c \{ C.s = f(\text{stack}[\text{top}-1]) \} \\ M &\rightarrow \varepsilon \{ M.s = \text{stack}[\text{top}-2] \} \end{aligned}$$

How to Add the Marker?

1. Identify the stack location(s) to find the desired attribute
2. Is there a conflict of location?
 - Yes, add a marker;
 - No, no need to add.
3. Add the marker in the place to remove location inconsistency

Example:

$S \rightarrow a A B C E D$

$S \rightarrow b A F B C F D$

$C \rightarrow c \text{ \textcolor{blue}{/* C.s = f(A.s) */}}$

$D \rightarrow d \text{ \textcolor{blue}{/* D.s = f(B.s) */}}$

Answer

$S \rightarrow a A B C E D$

$S \rightarrow b A D M B C F D$

$C \rightarrow c \text{ /* C.s = f(stack[top-2]) */}$

$D \rightarrow d \text{ /* D.s = f(stack[top-3]) */}$

$M \rightarrow \varepsilon \text{ /* M.s = f(stack[top-2]) */}$

 Regarding C.s, from stack[top-2], and stack[top-3]

.... add a Marker

 Regarding D.s, always from stack[top-2]

... no need to add

How about Top-Down Parsing?

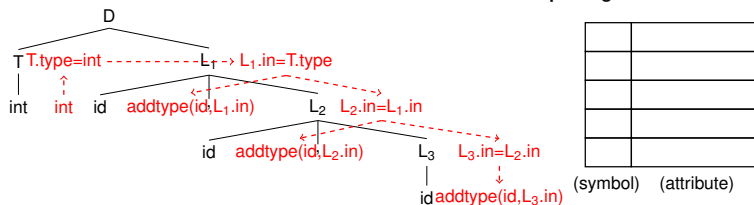
Translation Scheme for Top-Down Parsing

- Predictive Recursive Descent Parsers: Straightforward
 - Synthesized Attribute: Return value of function call for non-terminal is synthesized attribute
 - All function calls for children nodes would have completed by the time this function call returns
 - All dependent values would have been computed
 - Inherited Attribute: Pass as argument to function call for non-terminal inheriting attribute
 - L-Attributed grammar guarantees that dependent attributes come from left sibling attributes or parent inherited attributes
 - Left sibling function calls would have completed and parent inherited attribute would have been passed in as argument
 - All dependent values would have been computed
- Now let's focus on table-driven LL Parsers

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

it is natural to evaluate inherited attributes



Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

□ it is natural to evaluate inherited attributes

D

parsing stack:

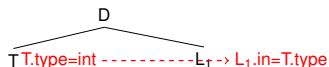
D	

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

- it is natural to evaluate inherited attributes



parsing stack:

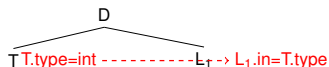
T	$T.type = int$
L_1	$L_1.in = ()$

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

- it is natural to evaluate inherited attributes



parsing stack:

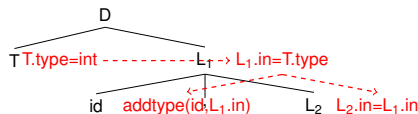
L_1	$L_1.in=int$

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

- it is natural to evaluate inherited attributes



parsing stack:

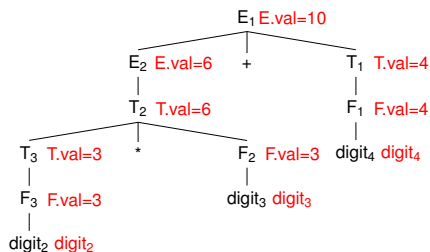
id	id.type=L ₁ .in
,	
L ₂	L ₂ .in=intL ₁ .in

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

it is **not natural** to evaluate synthesized attributes



parsing stack:

(symbol)	(attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

□ it is **not natural** to evaluate synthesized attributes

E_1

parsing stack:

E_1	

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

□ it is **not natural** to evaluate synthesized attributes

E_1 $E.val=?$

parsing stack:

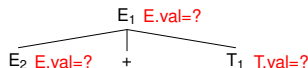
E_1	$E_1.val=?$

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

☐ it is **not natural** to evaluate synthesized attributes



parsing stack:

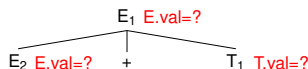
T ₁	T ₁ .val=?
+	
E ₂	E ₂ .val=?

(symbol) (attribute)

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

❑ it is **not natural** to evaluate synthesized attributes



parsing stack:

T ₁	T ₁ .val=?
+	
E ₂	E ₂ .val=?

(symbol) (attribute)

❑ Solution

- Always push a 'dummy' stack item below a non-terminal to hold intermediate values for attribute calculation
- Update dummy item whenever a child node is popped with intermediate value
- When all children nodes have been popped, compute synthesized attribute from stored values

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

❑ it is **not natural** to evaluate synthesized attributes

E_1

parsing stack:

E_1	
$E_1.val$???

(symbol) (attribute)

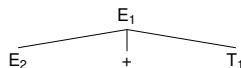
❑ Solution

- Always push a 'dummy' stack item below a non-terminal to hold intermediate values for attribute calculation
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- When all children nodes have been popped, compute synthesized attribute from stored values

Translation Scheme for LL Parsing

When using LL parsing (top-down parsing),

❑ it is **not natural** to evaluate synthesized attributes



parsing stack:

T ₁	
T ₁ .val	???
+	
E ₂	
E ₂ .val	???
E ₁ .val	E ₂ .val + T ₁ .val

(symbol) (attribute)

❑ Solution

- Always push a 'dummy' stack item below a non-terminal to hold intermediate values for attribute calculation
- Update dummy item whenever a child node is popped with intermediate value
- When all children nodes have been popped, compute synthesized attribute from stored values