Programming Languages and Compilers (CS 421)

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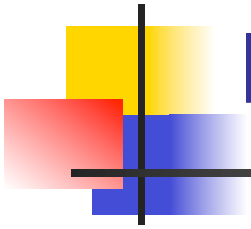
http://courses.engr.illinois.edu/cs421

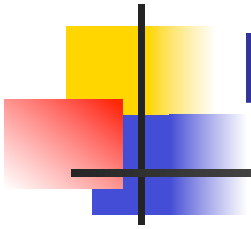
Based in part on slides by Mattox Beckman, as updated by Vikram Adve and Gul Agha

Disambiguating a Grammar



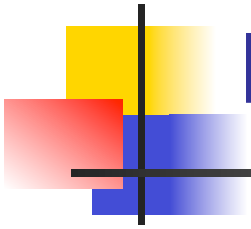
- <exp>::= 0|1| b<exp> | <exp>a
- | <exp>m<exp>
- Want a has higher precedence than b, which in turn has higher precedence than m, and such that m associates to the left.

Disambiguating a Grammar



- <exp>::= 0|1| b<exp> | <exp>a
- | <exp>m<exp>
- Want a has higher precedence than b, which in turn has higher precedence than m, and such that m associates to the left.
- <exp> ::= <exp> m <not m> | <not m>
- <not m> ::= b <not m> | <not b m>
- <not b m> ::= <not b m>a | 0 | 1

Disambiguating a Grammar – Take 2



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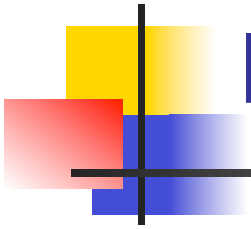
Disambiguating a Grammar – Take 2



- <exp>::= 0|1| b<exp> | <exp>a
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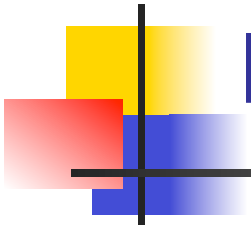
- Want b has higher precedence than m, which in turn has higher precedence than a, and such that m associates to the right.
- <exp> ::=
  <no a m> | <not m> m <no a>| <exp> a
- <no a> ::= <no a m> | <no a m> m <no a>
- <not m> ::= <no a m> | <exp> a
- <no a m> ::= b <no a m> | 0 | 1



LR Parsing

- Read tokens left to right (L)
- Create a rightmost derivation (R)
- How is this possible?
- Start at the bottom (left) and work your way up
- Last step has only one non-terminal to be replaced so is right-most
- Working backwards, replace mixed strings by non-terminals
- Always proceed so that there are no non-terminals to the right of the string to be replaced

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> =>

= ● (0 + 1) + 0 shift

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

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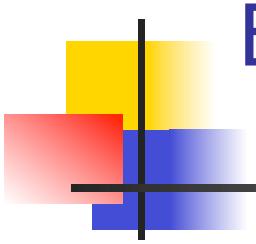
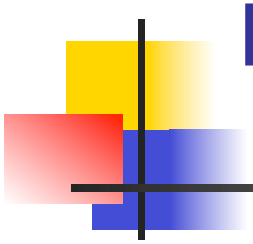


<Sum> =>

=> (0 ● + 1) + 0	reduce
= (● 0 + 1) + 0	shift
= ● (0 + 1) + 0	shift

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>



<Sum> =>

= (<Sum> ● + 1) + 0	shift
=> (0 ● + 1) + 0	reduce
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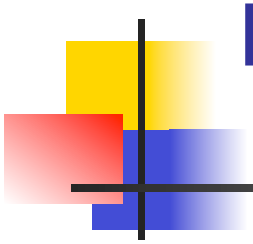
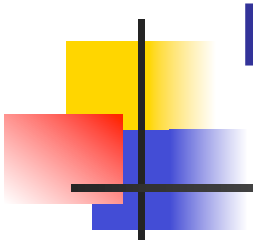
Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>



<Sum> =>

=	(<Sum> + ● 1) + 0	shift
=	(<Sum> ● + 1) + 0	shift
=>	(0 ● + 1) + 0	reduce
=	(● 0 + 1) + 0	shift
=	● (0 + 1) + 0	shift

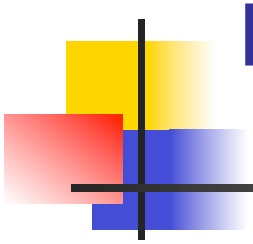
Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>



<Sum> =>

=> (<Sum> + 1 ●) + 0	reduce
= (<Sum> + ● 1) + 0	shift
= (<Sum> ● + 1) + 0	shift
=> (0 ● + 1) + 0	reduce
= (● 0 + 1) + 0	shift
= ● (0 + 1) + 0	shift

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>



<Sum> =>

=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
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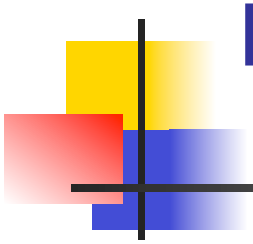
Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>



<Sum> =>

= (<Sum> ●) + 0 shift
=> (<Sum> + <Sum> ●) + 0 reduce
=> (<Sum> + 1 ●) + 0 reduce
= (<Sum> + ● 1) + 0 shift
= (<Sum> ● + 1) + 0 shift
=> (0 ● + 1) + 0 reduce
= (● 0 + 1) + 0 shift
= ● (0 + 1) + 0 shift

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> =>

=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
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Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> =>

= <Sum> ● + 0	shift
=> (<Sum>) ● + 0	reduce
= (<Sum> ●) + 0	shift
=> (<Sum> + <Sum> ●) + 0	reduce
=> (<Sum> + 1 ●) + 0	reduce
= (<Sum> + ● 1) + 0	shift
= (<Sum> ● + 1) + 0	shift
=> (0 ● + 1) + 0	reduce
= (● 0 + 1) + 0	shift
= ● (0 + 1) + 0	shift

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> =>

= <Sum> + ● 0	shift
= <Sum> ● + 0	shift
=> (<Sum>) ● + 0	reduce
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Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> =>

=> <Sum> + 0 ● reduce

= <Sum> + ● 0 shift

= <Sum> ● + 0 shift

=> (<Sum>) ● + 0 reduce

= (<Sum> ●) + 0 shift

=> (<Sum> + <Sum> ●) + 0 reduce

=> (<Sum> + 1 ●) + 0 reduce

= (<Sum> + ● 1) + 0 shift

= (<Sum> ● + 1) + 0 shift

=> (0 ● + 1) + 0 reduce

= (● 0 + 1) + 0 shift

= ● (0 + 1) + 0 shift

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> => <Sum> + <Sum > ● reduce
=> <Sum> + 0 ● reduce
= <Sum> + ● 0 shift
= <Sum> ● + 0 shift
=> (<Sum>) ● + 0 reduce
= (<Sum> ●) + 0 shift
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Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

<Sum> ● => <Sum> + <Sum > ● reduce
=> <Sum> + 0 ● reduce
= <Sum> + ● 0 shift
= <Sum> ● + 0 shift
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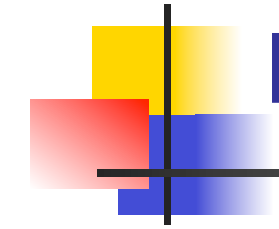
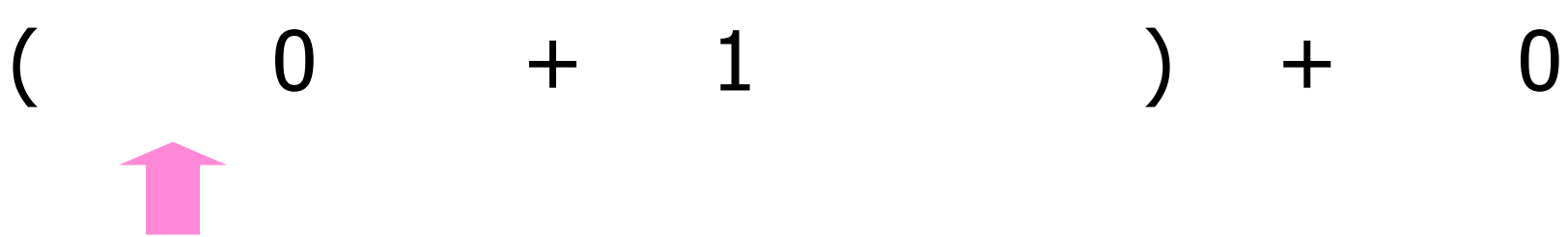
Example



(0 + 1) + 0

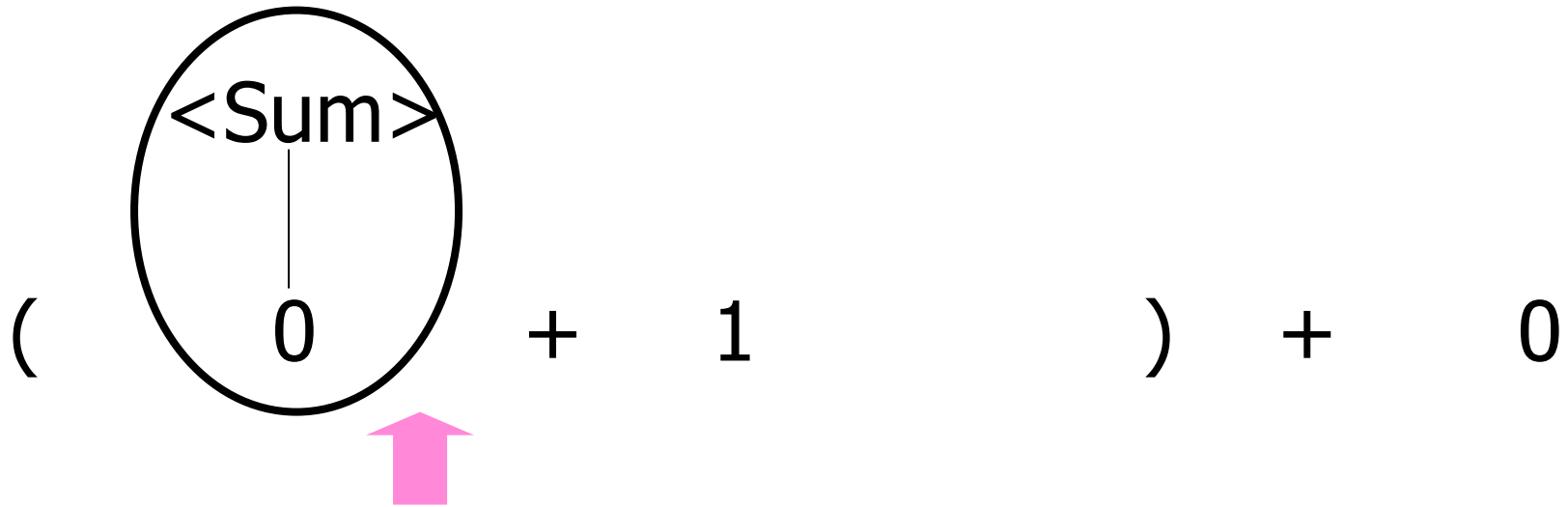
Example



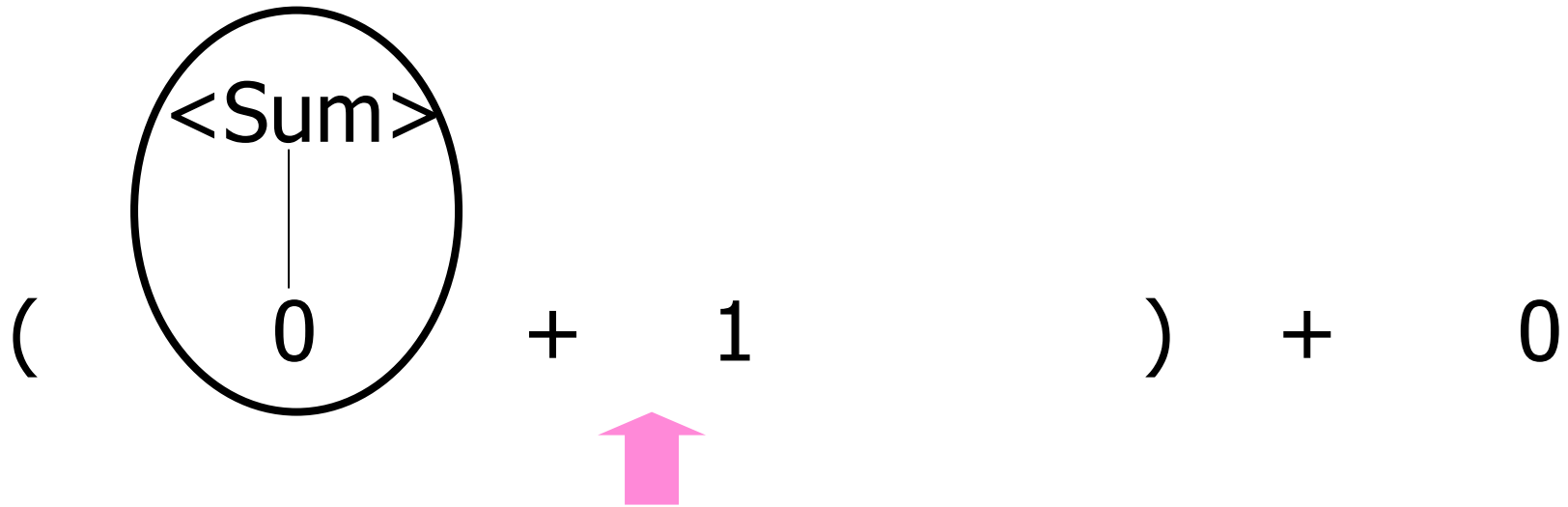
Example

(0 + 1) + 0

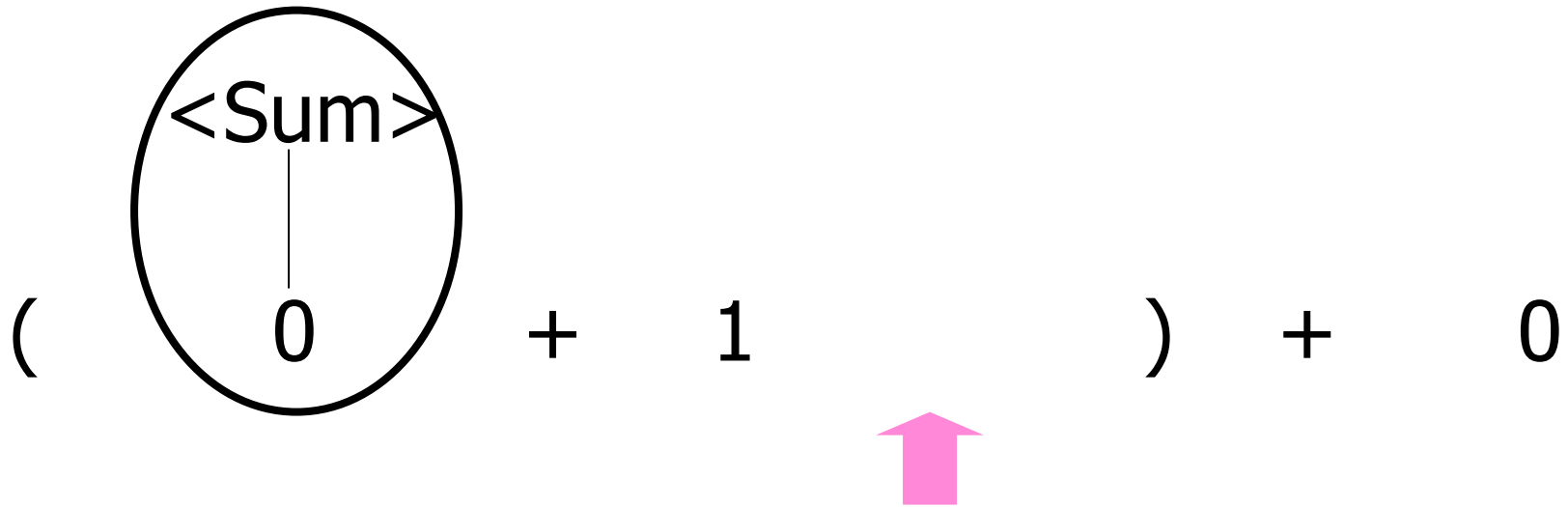
Example



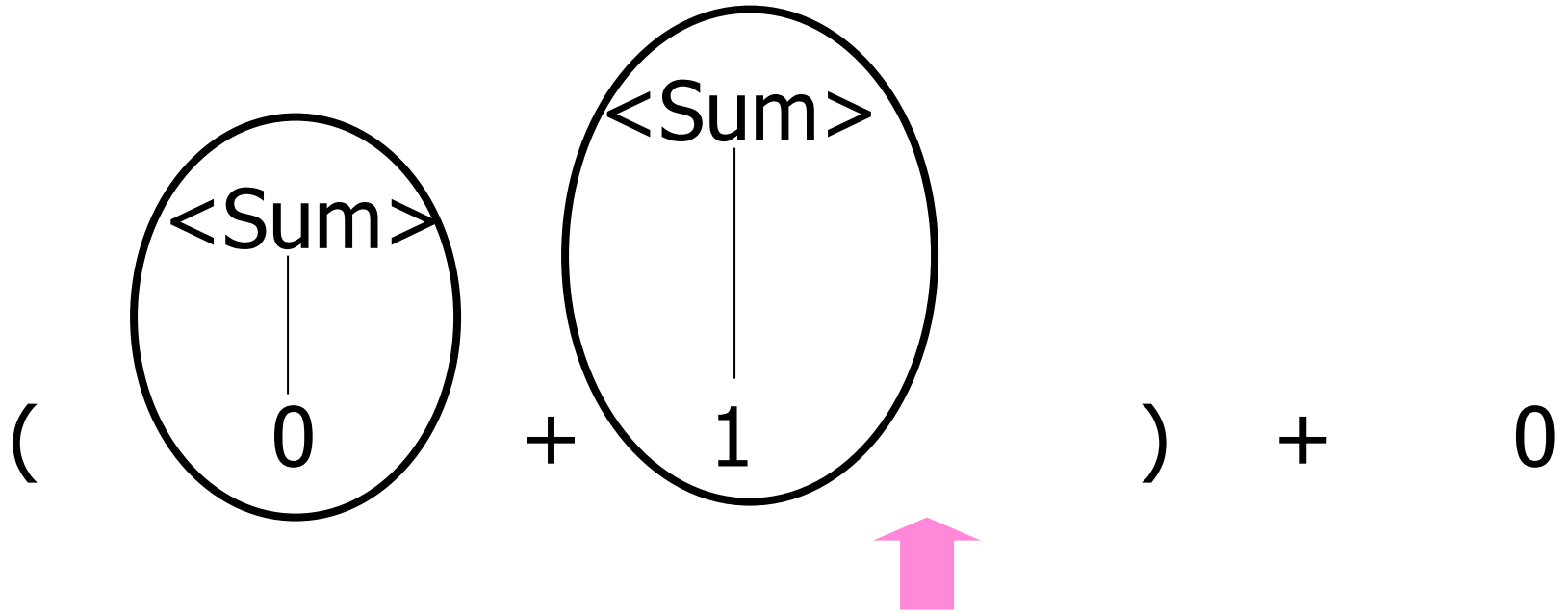
Example



Example



Example



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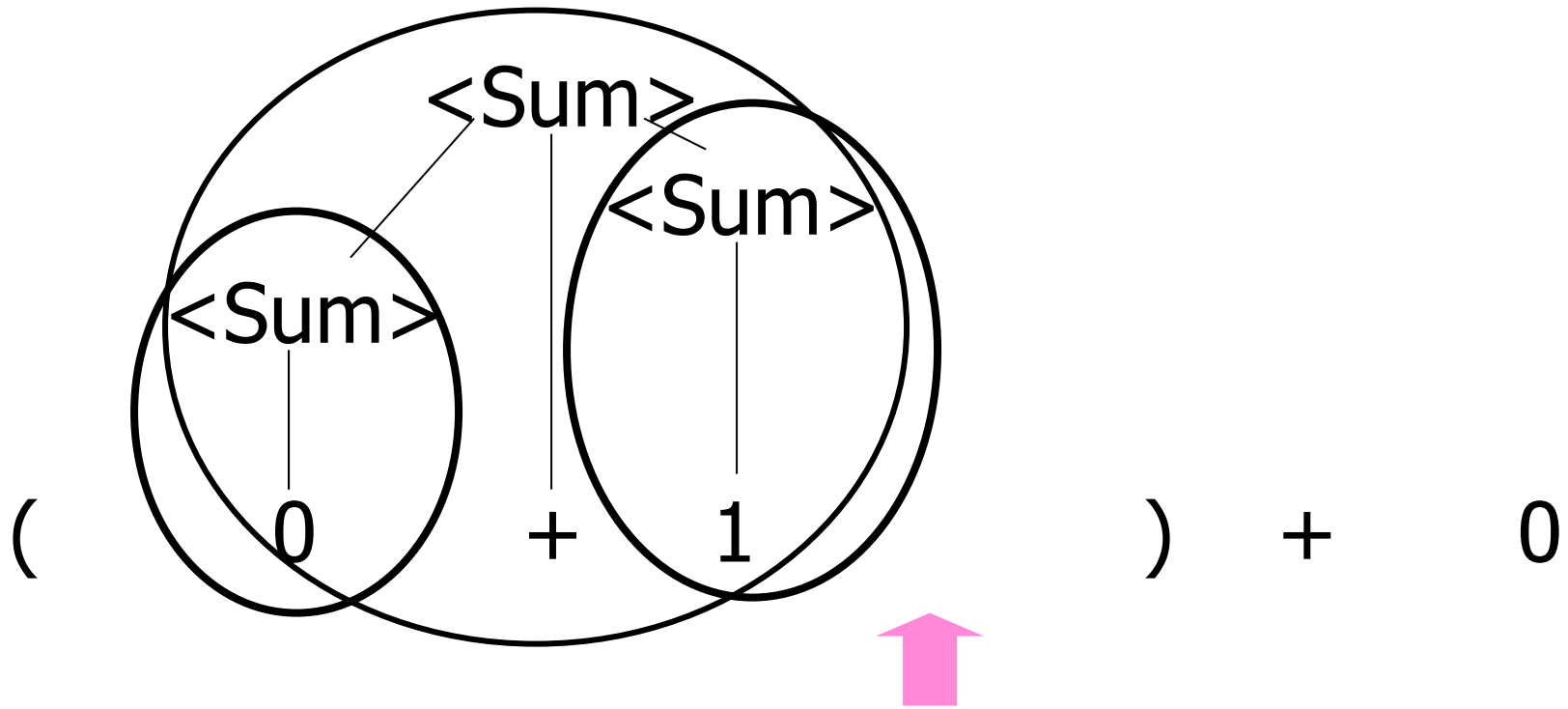

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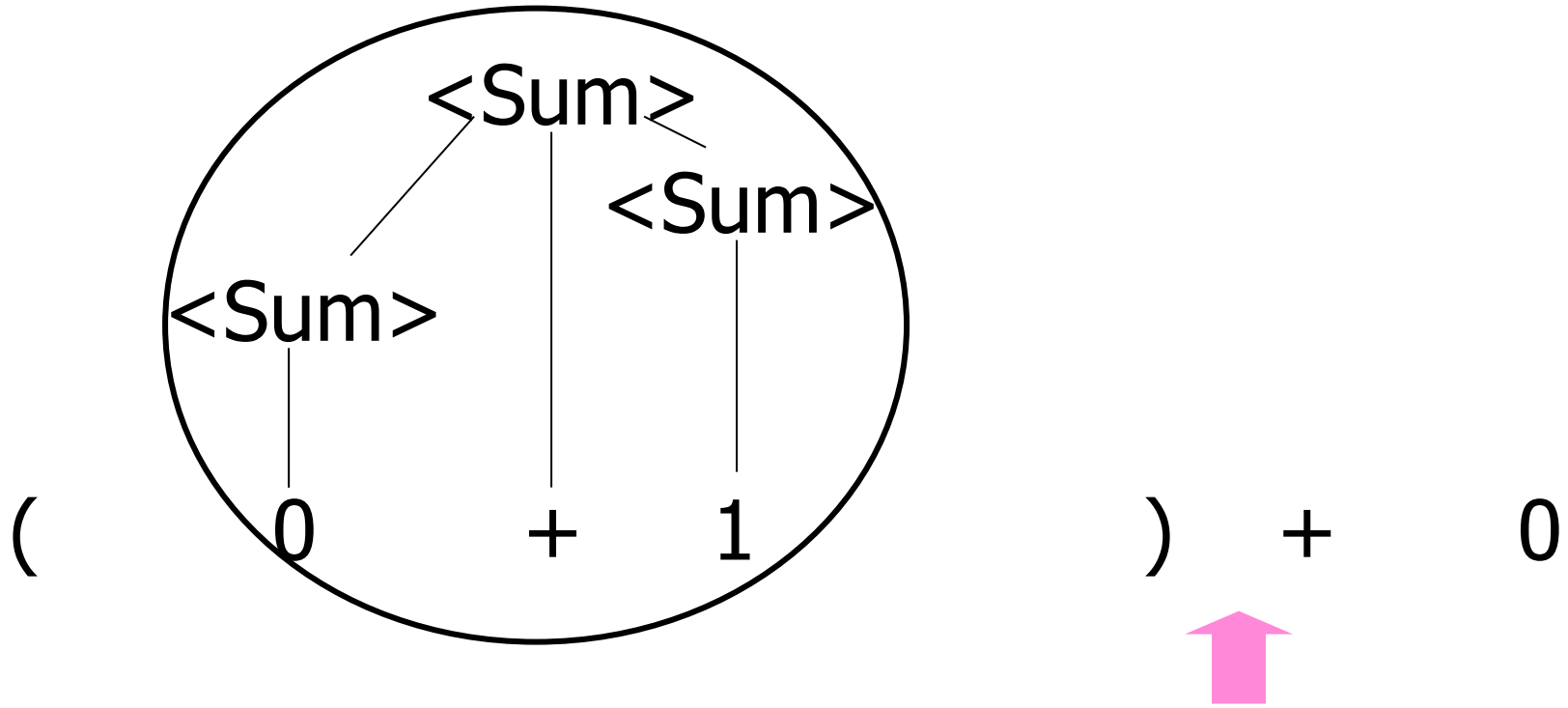

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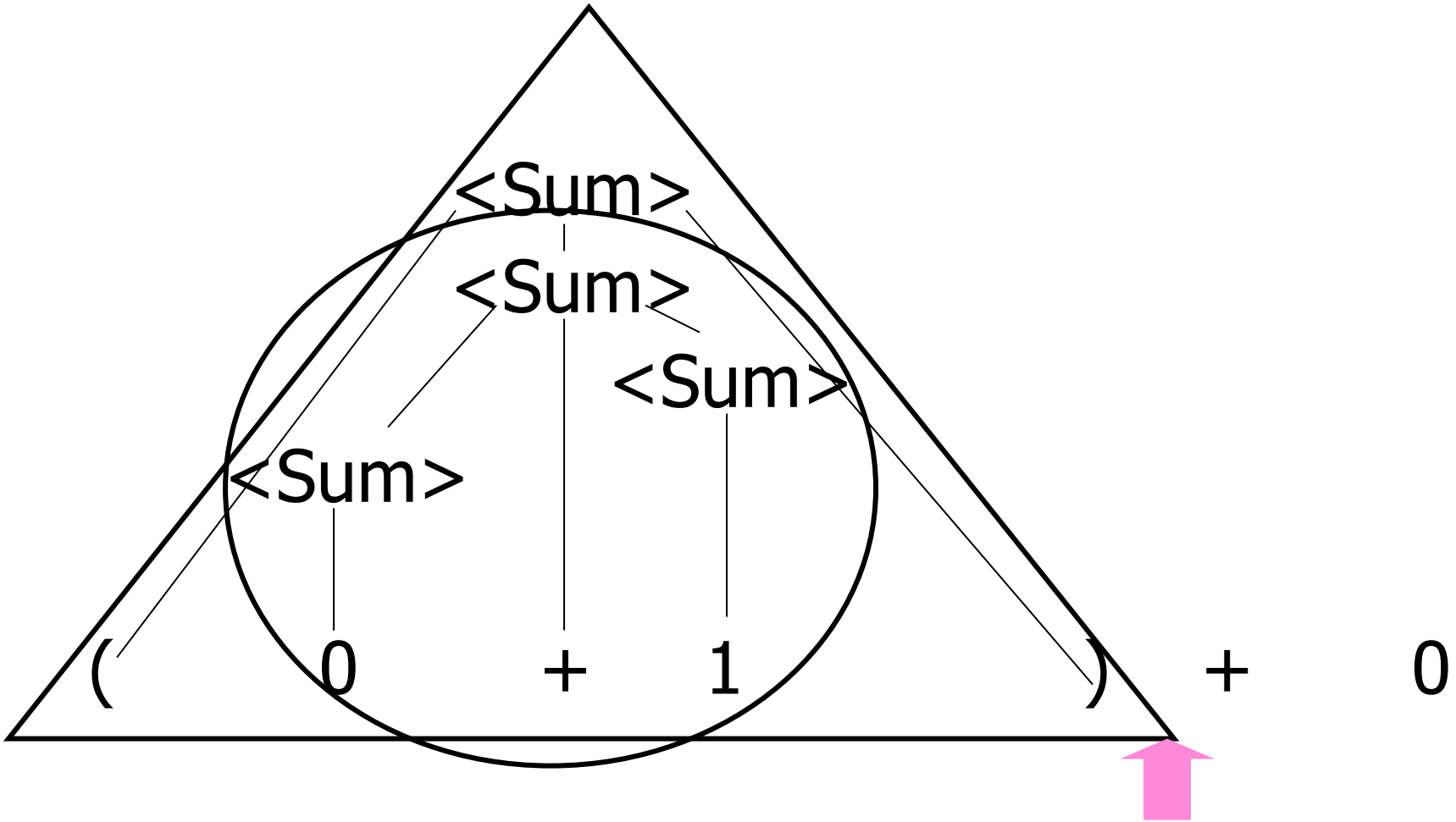

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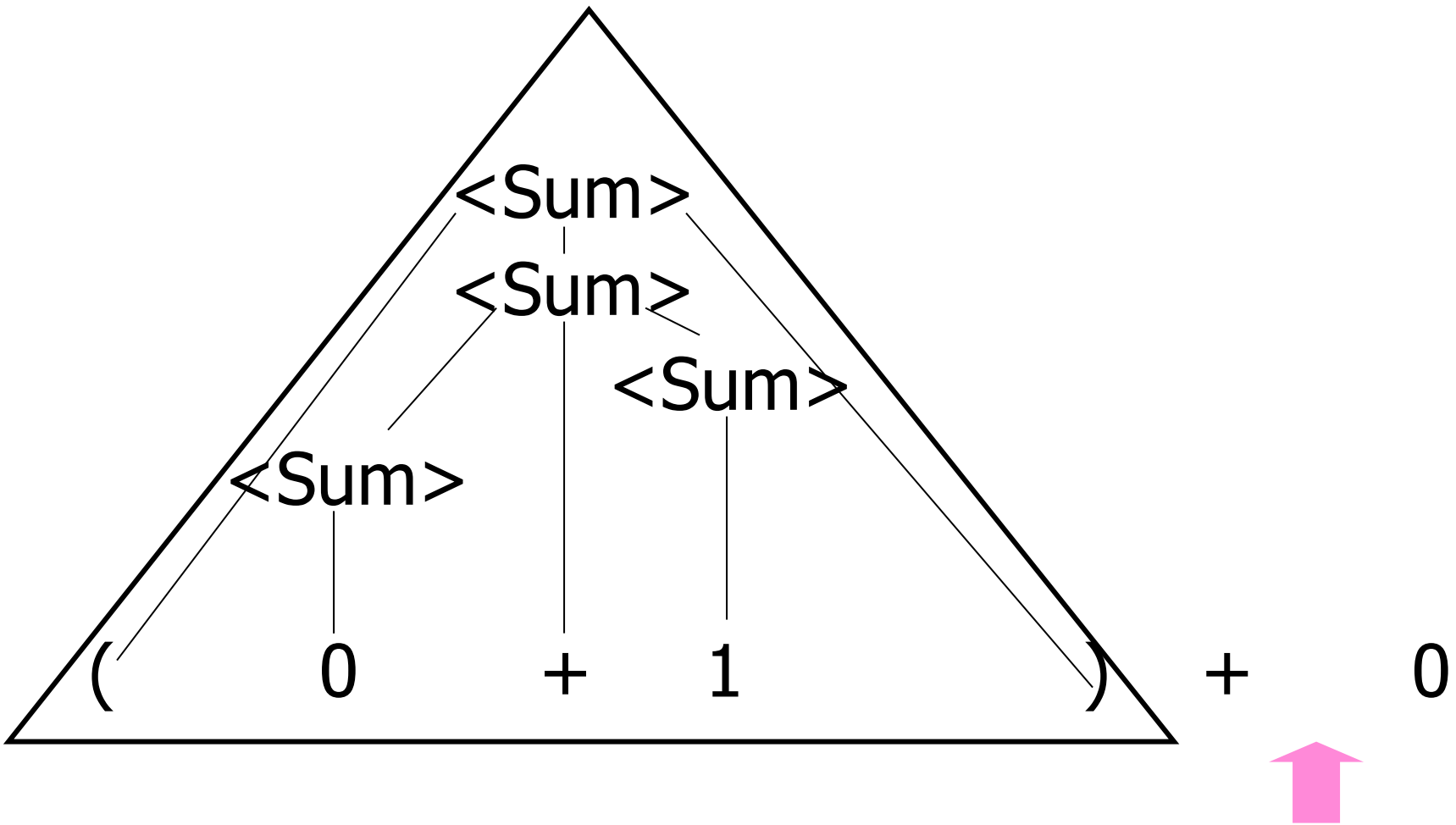

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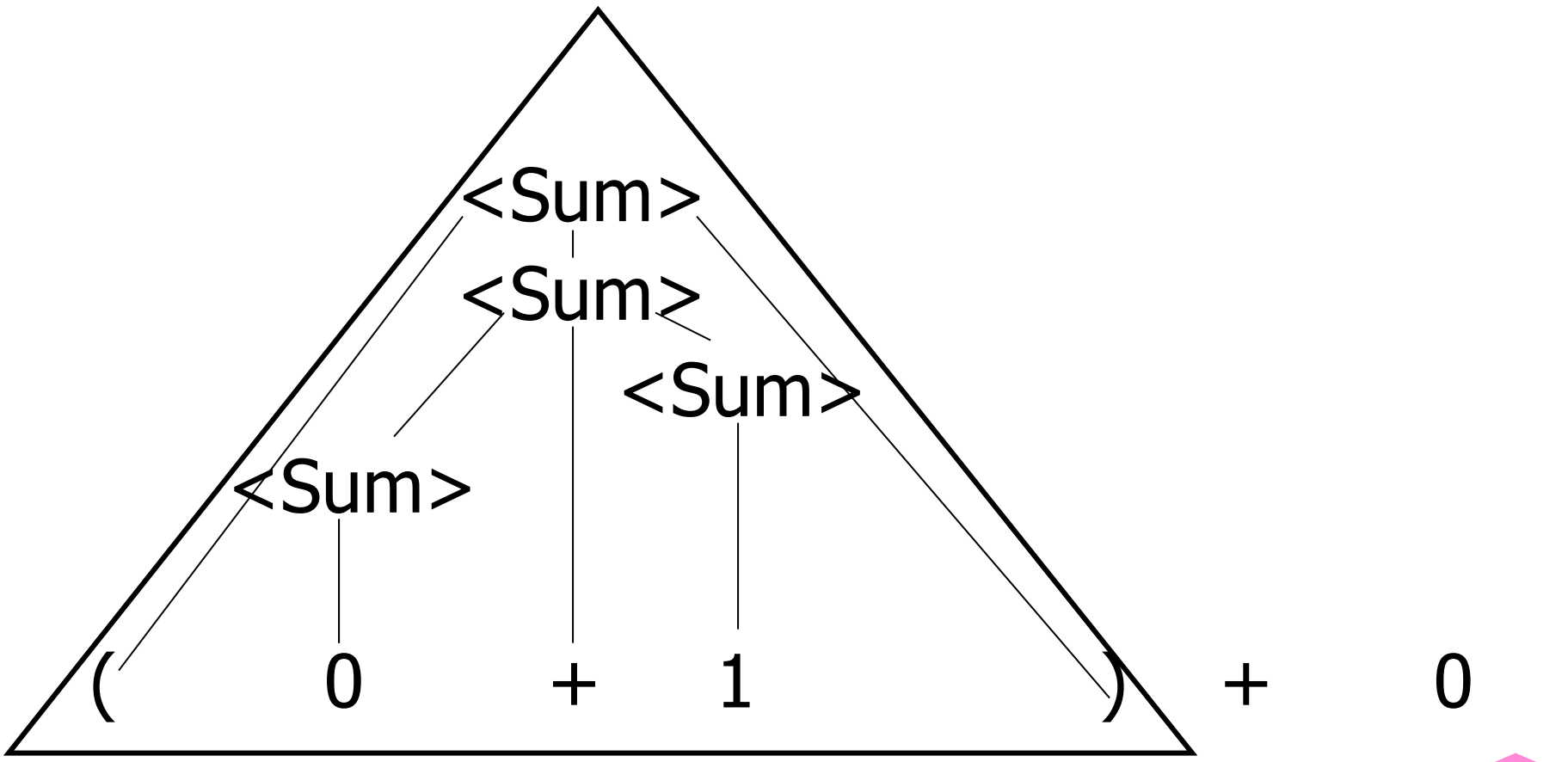

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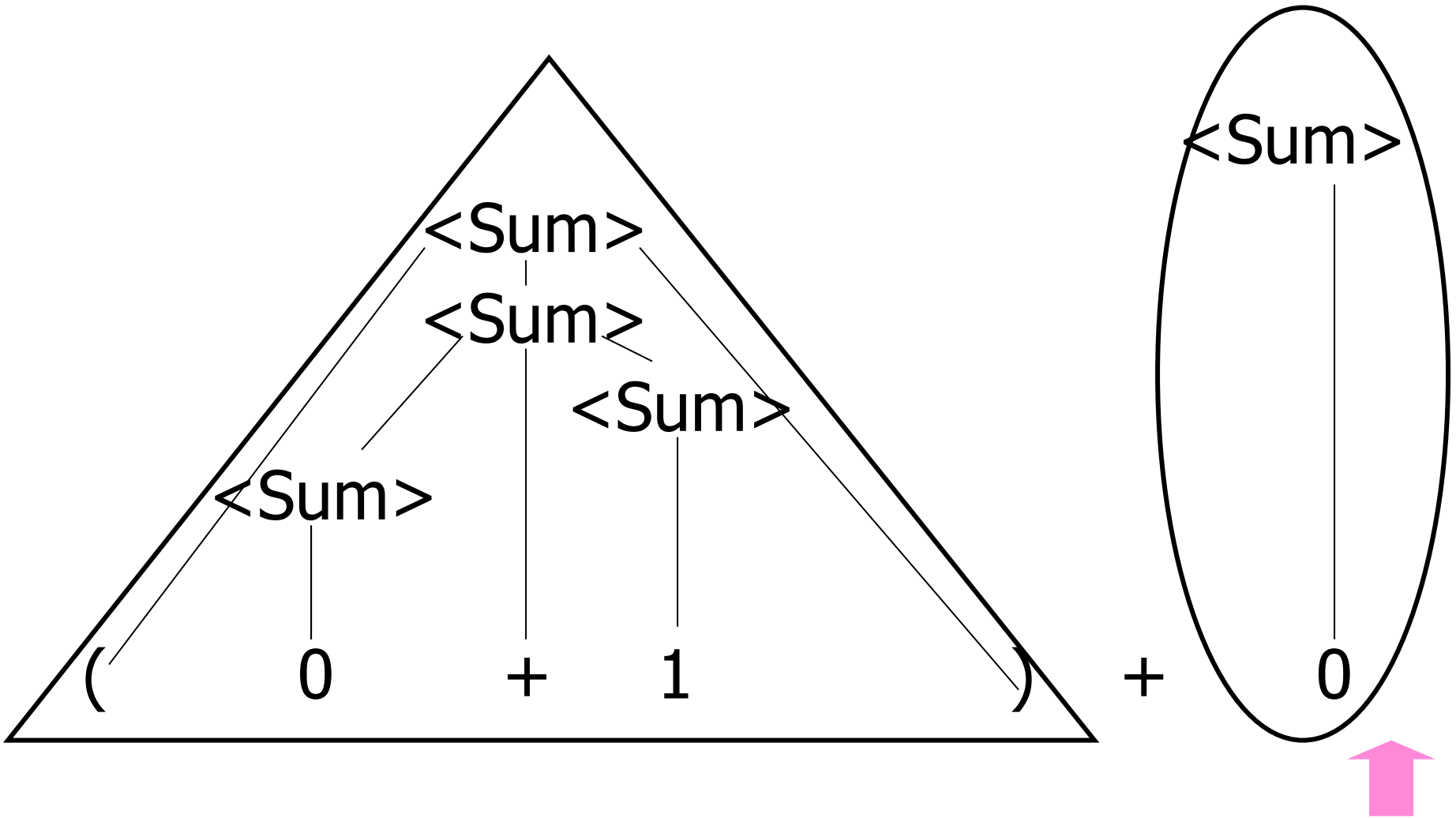

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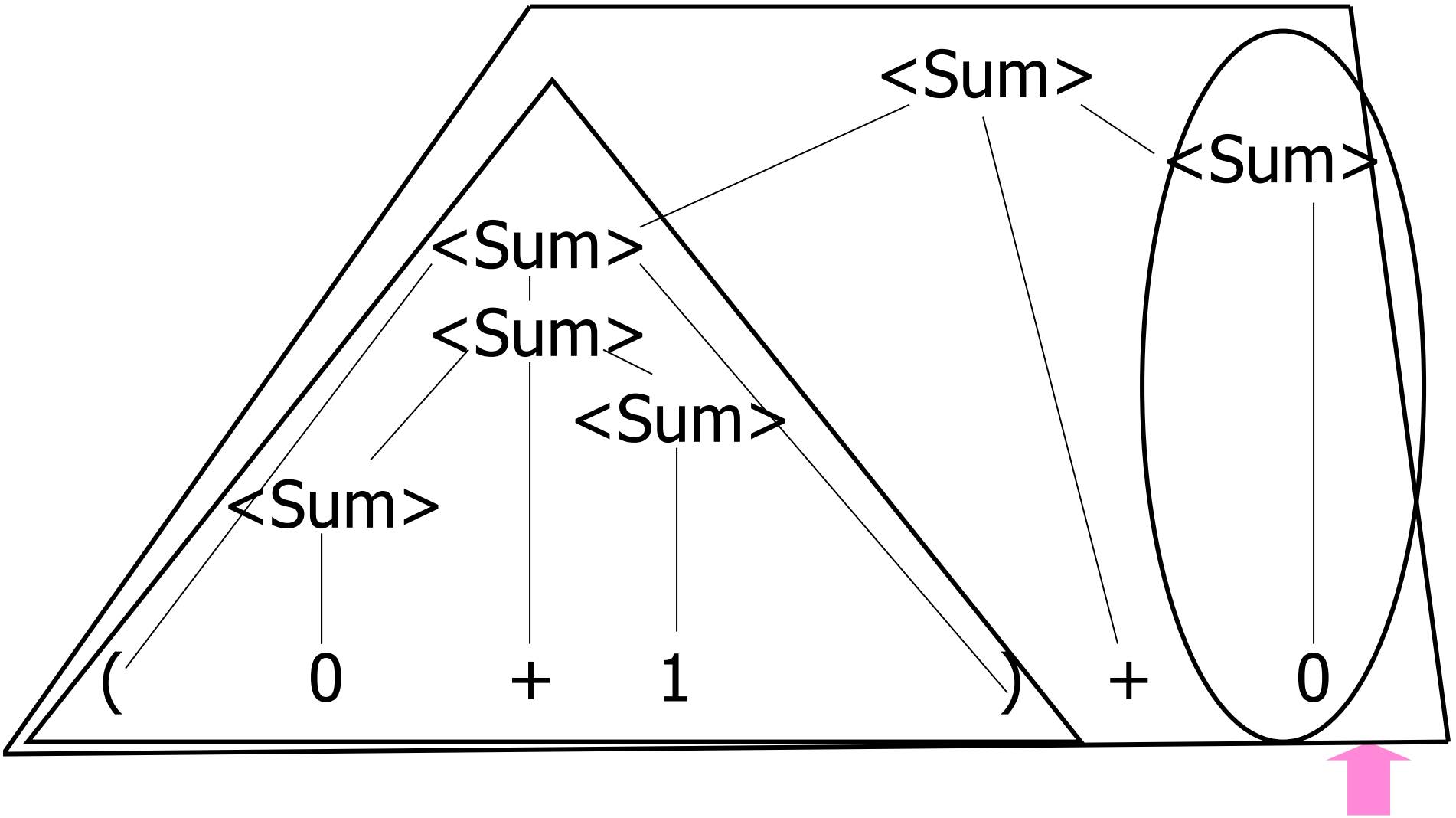

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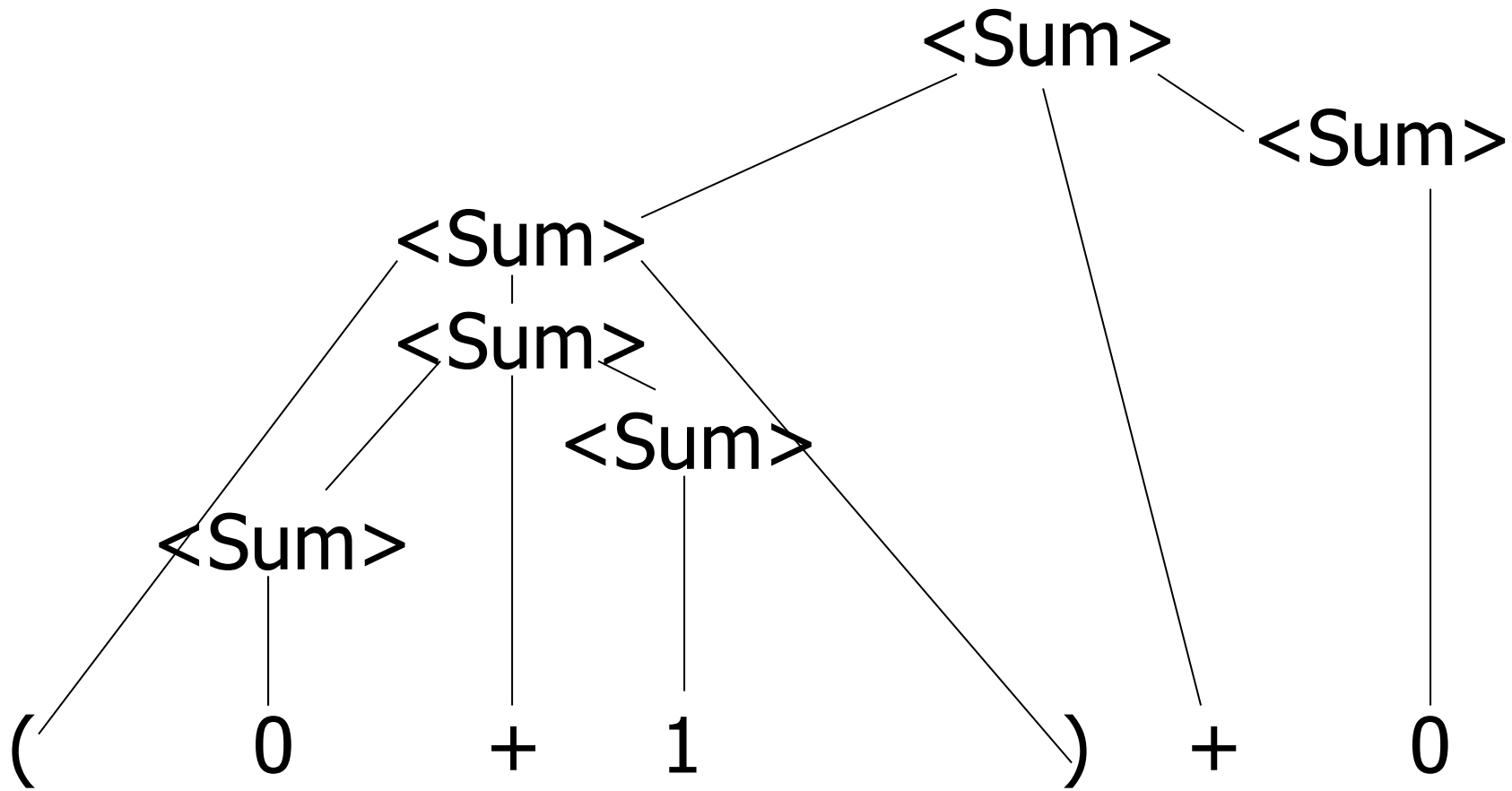
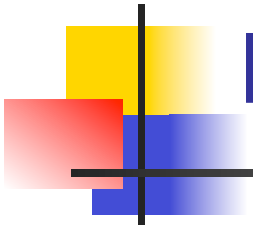
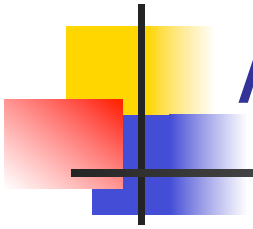




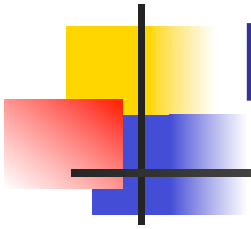
LR Parsing Tables

- Build a pair of tables, Action and Goto, from the grammar
  - This is the hardest part, we omit here
  - Rows labeled by states
  - For Action, columns labeled by terminals and “end-of-tokens” marker
    - (more generally strings of terminals of fixed length)
  - For Goto, columns labeled by non-terminals



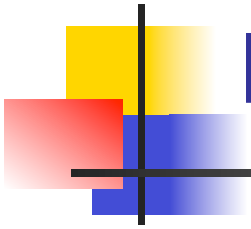
Action and Goto Tables

- Given a state and the next input, Action table says either
  - **shift** and go to state *n*, or
  - **reduce** by production *k* (explained in a bit)
  - **accept** or **error**
- Given a state and a non-terminal, Goto table says
  - go to state *m*



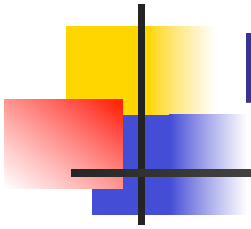
LR(i) Parsing Algorithm

- Based on push-down automata
- Uses states and transitions (as recorded in Action and Goto tables)
- Uses a stack containing states, terminals and non-terminals



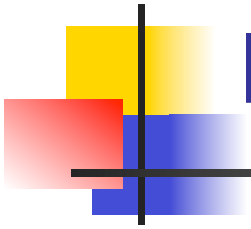
LR(i) Parsing Algorithm

0. Insure token stream ends in special "end-of-tokens" symbol
1. Start in state 1 with an empty stack
2. Push **state**(1) onto stack
3. Look at next *i* tokens from token stream (*toks*) (don't remove yet)
4. If top symbol on stack is **state**(*n*), look up action in Action table at (*n*, *toks*)



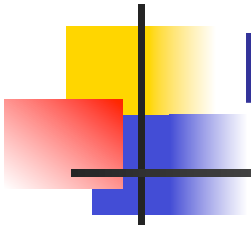
LR(i) Parsing Algorithm

5. If action = **shift** *m*,
   a) Remove the top token from token stream and push it onto the stack
   b) Push **state**(*m*) onto stack
   c) Go to step 3



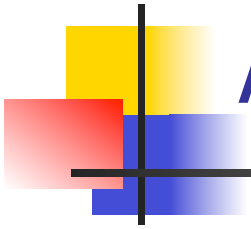
LR(i) Parsing Algorithm

6. If action = **reduce** *k* where production *k* is E ::= u
   a) Remove 2 * length(u) symbols from stack (u and all the interleaved states)
   b) If new top symbol on stack is **state**(*m*), look up new state *p* in Goto(*m*,E)
   c) Push E onto the stack, then push **state**(*p*) onto the stack
   d) Go to step 3



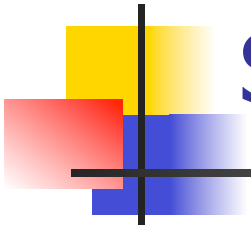
LR(i) Parsing Algorithm

7. If action = **accept**
   - Stop parsing, return success
8. If action = **error**,
   - Stop parsing, return failure



Adding Synthesized Attributes

- Add to each **reduce** a rule for calculating the new synthesized attribute from the component attributes
- Add to each non-terminal pushed onto the stack, the attribute calculated for it
- When performing a **reduce**,
  - gather the recorded attributes from each non-terminal popped from stack
  - Compute new attribute for non-terminal pushed onto stack

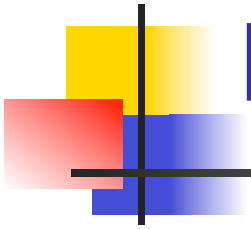


Shift-Reduce Conflicts

- **Problem**: can't decide whether the action for a state and input character should be **shift** or **reduce**
- Caused by ambiguity in grammar
- Usually caused by lack of associativity or precedence information in grammar

Example: <Sum> = 0 | 1 | (<Sum>) | <Sum> + <Sum>

● 0 + 1 + 0	shift
-> 0 ● + 1 + 0	reduce
-> <Sum> ● + 1 + 0	shift
-> <Sum> + ● 1 + 0	shift
-> <Sum> + 1 ● + 0	reduce
-> <Sum> + <Sum> ● + 0	

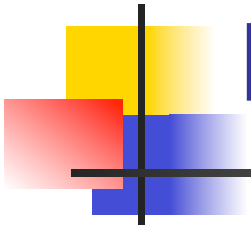


Example - cont

- **Problem:** shift or reduce?

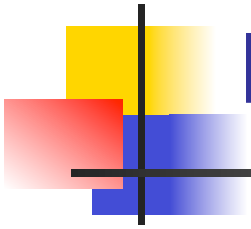
- You can shift-shift-reduce-reduce or reduce-shift-shift-reduce

- Shift first - right associative
- Reduce first- left associative



Reduce - Reduce Conflicts

- **Problem:** can't decide between two different rules to reduce by
- Again caused by ambiguity in grammar
- **Symptom:** RHS of one production suffix of another
- Requires examining grammar and rewriting it
- Harder to solve than shift-reduce errors

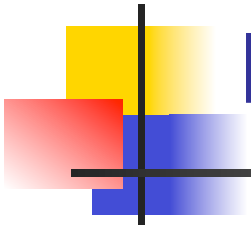


Example

- S ::= A | aB A ::= abc B ::= bc

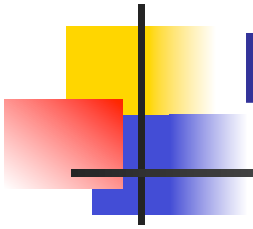
  - ● abc shift
  - a ● bc shift
  - ab ● c shift
  - abc ●

- Problem: reduce by B ::= bc then by S ::= aB, or by A::= abc then S::A?



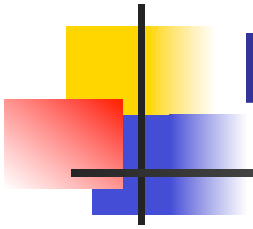
Recursive Descent Parsing

- Recursive descent parsers are a class of parsers derived fairly directly from BNF grammars
- A recursive descent parser traces out a parse tree in top-down order, corresponding to a left-most derivation (LL - left-to-right scanning, leftmost derivation)



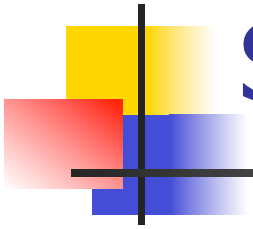
Recursive Descent Parsing

- Each nonterminal in the grammar has a subprogram associated with it; the subprogram parses all phrases that the nonterminal can generate
- Each nonterminal in right-hand side of a rule corresponds to a recursive call to the associated subprogram



Recursive Descent Parsing

- Each subprogram must be able to decide how to begin parsing by looking at the left-most character in the string to be parsed
  - May do so directly, or indirectly by calling another parsing subprogram
- Recursive descent parsers, like other top-down parsers, cannot be built from left-recursive grammars
  - Sometimes can modify grammar to suit

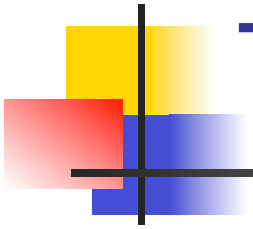


Sample Grammar

<expr> ::= <term> | <term> + <expr>
| <term> - <expr>

<term> ::= <factor> | <factor> * <term>
| <factor> / <term>

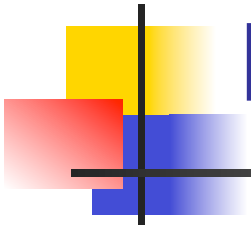
<factor> ::= <id> | (<expr>)



Tokens as OCaml Types

- + - * / ( ) <id>
- Becomes an OCaml datatype

```
type token =
    Id_token of string
  | Left_parenthesis | Right_parenthesis
  | Times_token | Divide_token
  | Plus_token | Minus_token
```



Parse Trees as Datatypes

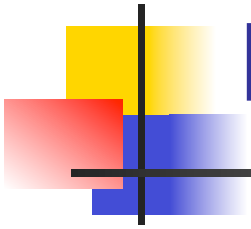
<expr> ::= <term> | <term> + <expr>
| <term> - <expr>

```
type expr =
    Term_as_Expr of term
  | Plus_Expr of (term * expr)
  | Minus_Expr of (term * expr)
```

Parse Trees as Datatypes

<term> ::= <factor> | <factor> * <term>
| <factor> / <term>

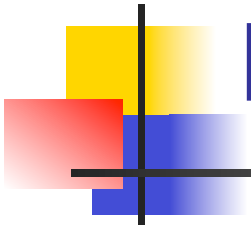
and term =
Factor_as_Term of factor
| Mult_Term of (factor * term)
| Div_Term of (factor * term)



Parse Trees as Datatypes

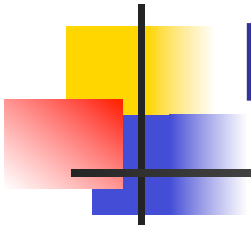
<factor> ::= <id> | (<expr>)

```
and factor =
    Id_as_Factor of string
  | Parenthesized_Expr_as_Factor of expr
```



Parsing Lists of Tokens

- Will create three mutually recursive functions:
  - expr : token list -> (expr * token list)
  - term : token list -> (term * token list)
  - factor : token list -> (factor * token list)
- Each parses what it can and gives back parse and remaining tokens



Parsing an Expression

<expr> ::= <term> [(+ | -) <expr>]

```
let rec expr tokens =
  (match term tokens
    with ( term_parse , tokens_after_term) ->
      (match tokens_after_term
        with( Plus_token  :: tokens_after_plus) ->
```

Parsing an Expression

<expr> ::= <term> [(+ | -) <expr>]

```
let rec expr tokens =
  (match term tokens
    with ( term_parse , tokens_after_term) ->
      (match tokens_after_term
       with ( Plus_token  :: tokens_after_plus) ->
```

Parsing a Plus Expression

<expr> ::= <term> [(+ | -) <expr>]

```
let rec expr tokens =
  (match term tokens
    with ( term_parse , tokens_after_term) ->
      (match tokens_after_term
       with ( Plus_token  :: tokens_after_plus) ->
```

Parsing a Plus Expression

<expr> ::= <term> [(+ | -) <expr>]

```
let rec expr tokens =
  (match term tokens
    with ( term_parse , tokens_after_term) ->
      (match tokens_after_term
       with ( Plus_token  :: tokens_after_plus) ->
```

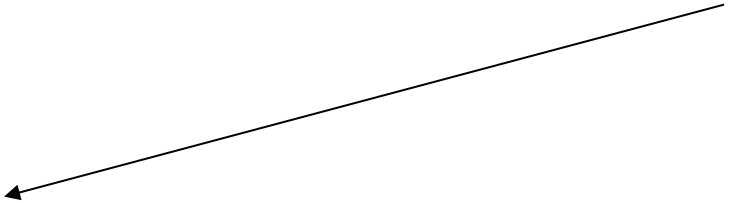
Parsing a Plus Expression

<expr> ::= <term> [(+ | -) <expr>]

```
let rec expr tokens =
  (match term tokens
    with ( term_parse , tokens_after_term) ->
      (match tokens_after_term
       with ( Plus_token  :: tokens_after_plus) ->
```

Parsing a Plus Expression

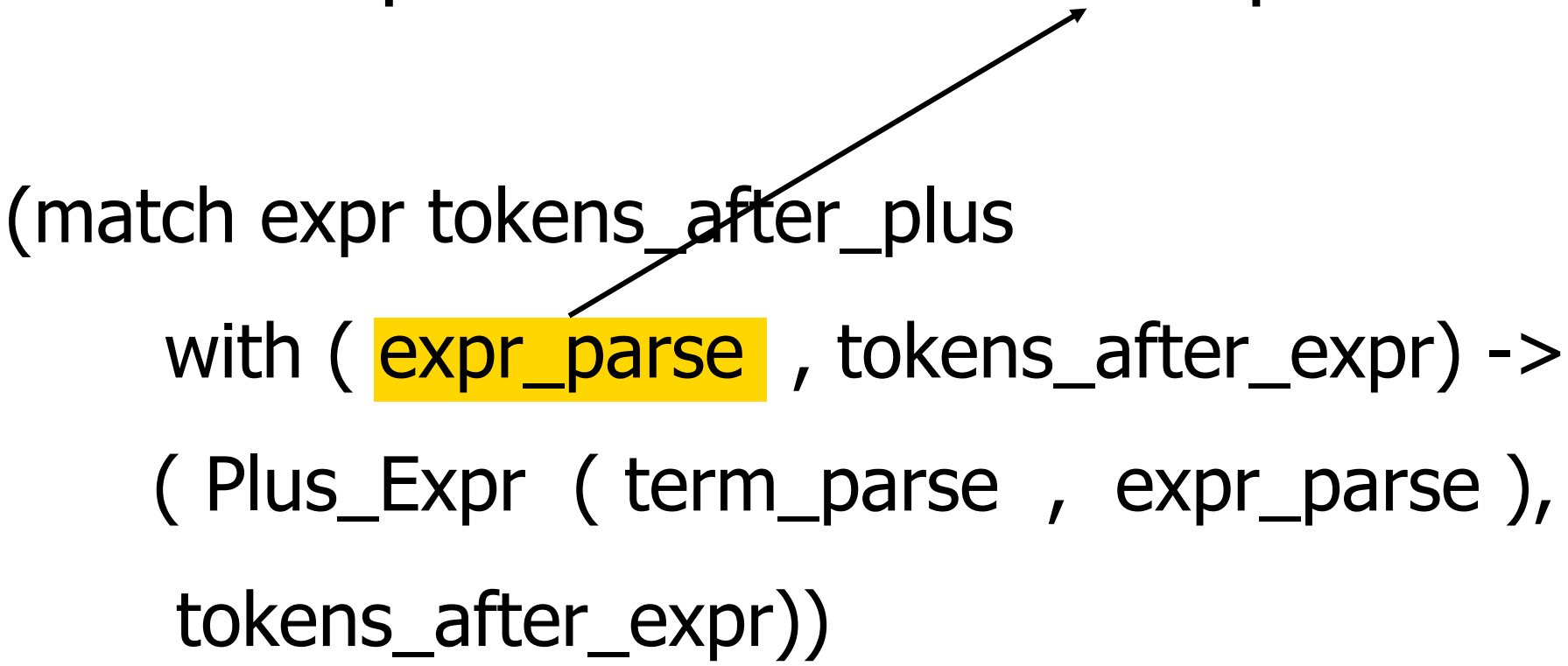
<expr> ::= <term> + <expr>



```
(match expr tokens_after_plus
 with ( expr_parse  , tokens_after_expr) ->
( Plus_Expr  ( term_parse  ,  expr_parse ),
 tokens_after_expr))
```

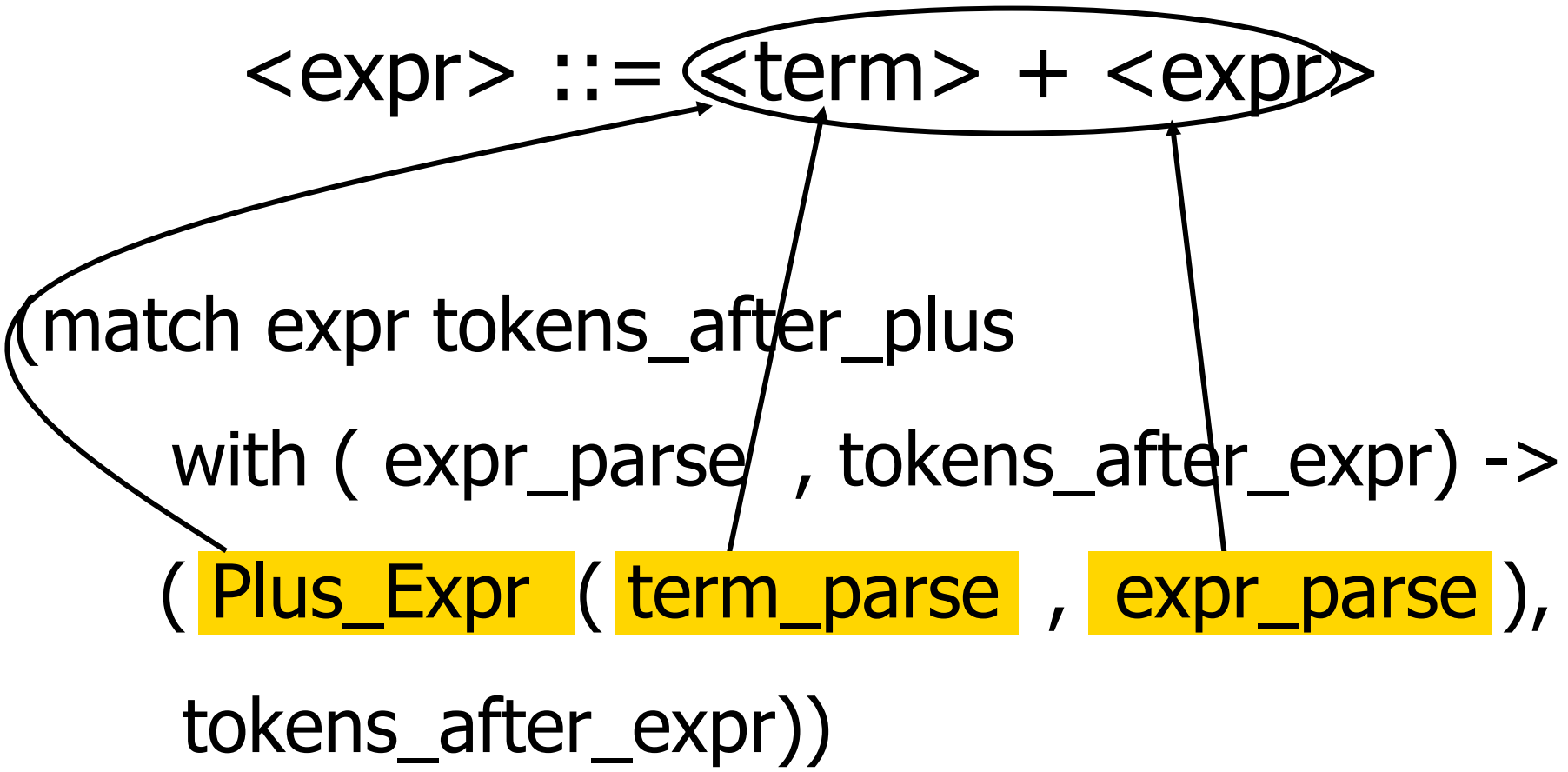
Parsing a Plus Expression

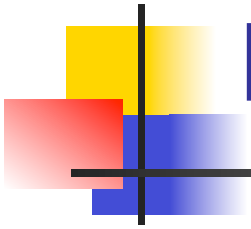
<expr> ::= <term> + <expr>



```
(match expr tokens_after_plus
      with ( expr_parse , tokens_after_expr) ->
     ( Plus_Expr  ( term_parse  ,  expr_parse ),
      tokens_after_expr))
```

Building Plus Expression Parse Tree



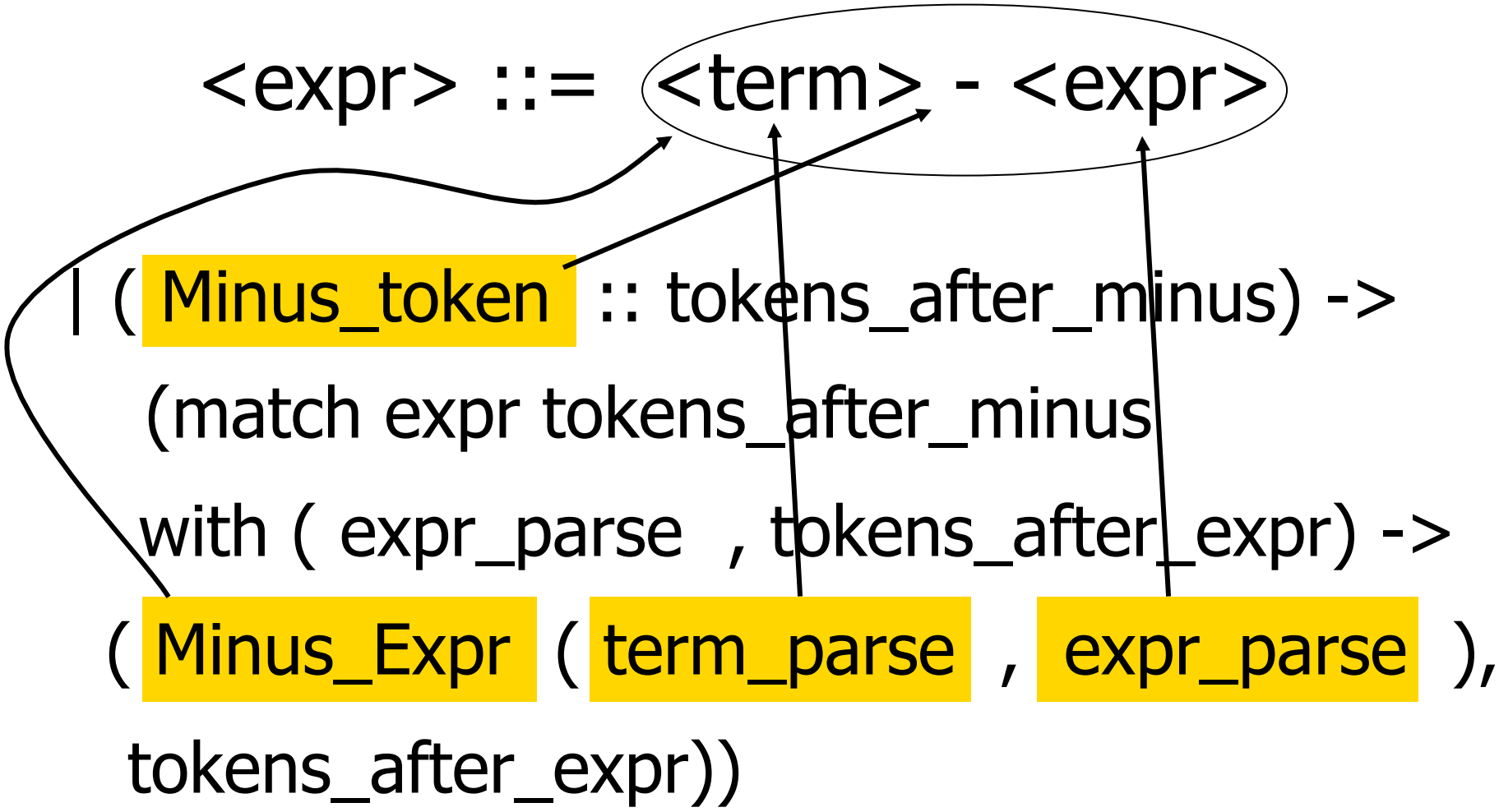


Parsing a Minus Expression

<expr> ::= <term> - <expr>

```
| ( Minus_token  :: tokens_after_minus) ->
   (match expr tokens_after_minus
   with ( expr_parse  , tokens_after_expr) ->
  ( Minus_Expr  ( term_parse  ,  expr_parse  ),
   tokens_after_expr))
```

Parsing a Minus Expression



Parsing an Expression as a Term

<expr> ::= <term>

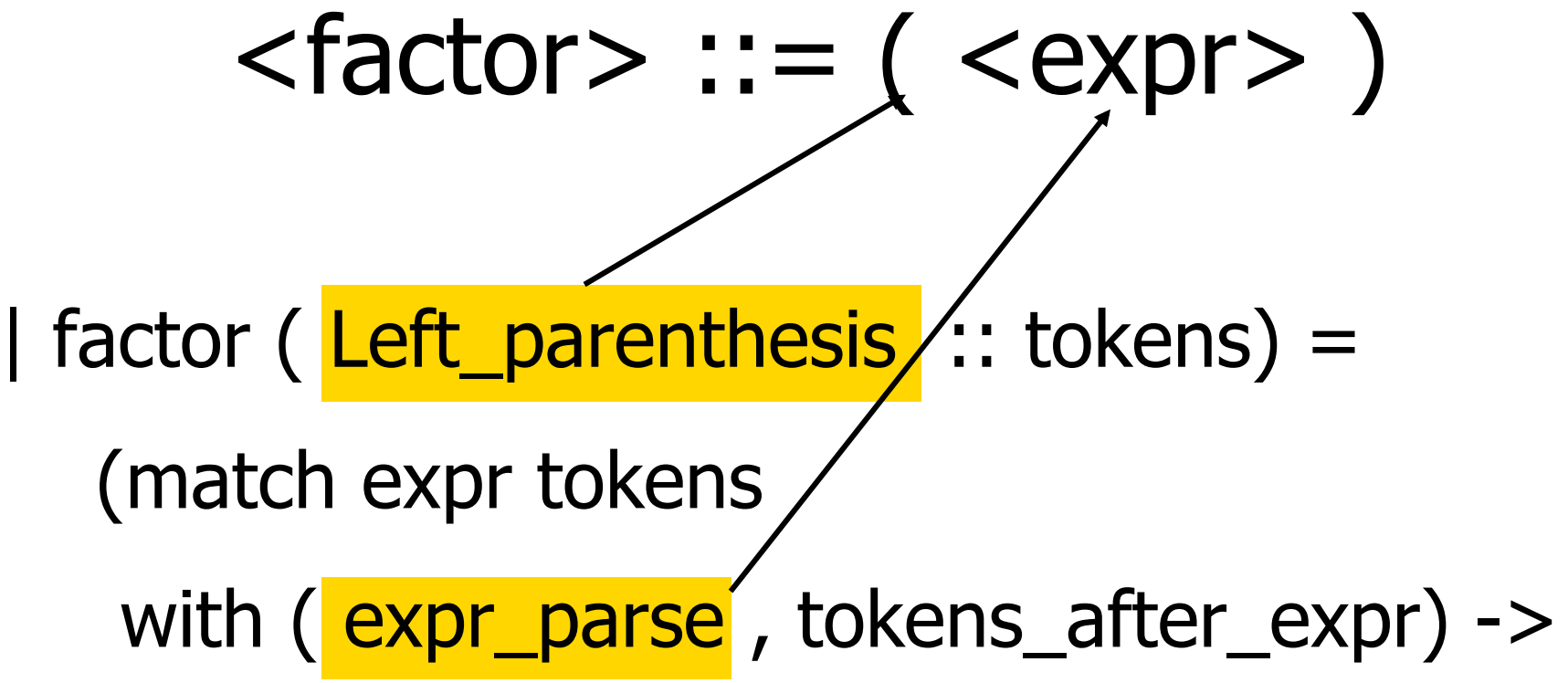
| _ -> (Term_as_Expr term_parse ,
tokens_after_term)))

- Code for **term** is same except for replacing addition with multiplication and subtraction with division

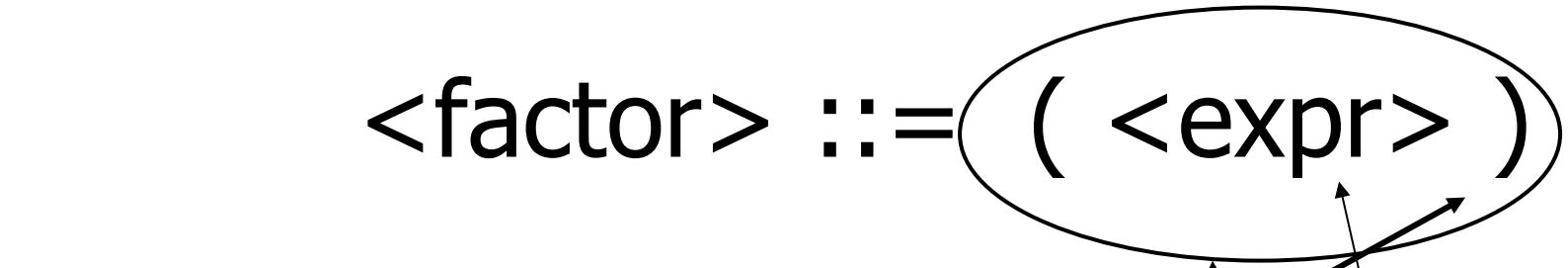
Parsing Factor as Id


```
and factor  tokens =
 (match tokens
  with (Id_token id_name :: tokens_after_id) =
   ( Id_as_Factor  id_name, tokens_after_id)
```

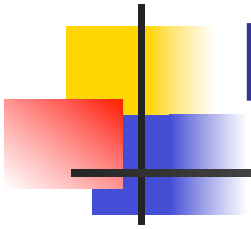
Parsing Factor as Parenthesized Expression



Parsing Factor as Parenthesized Expression




```
(match tokens_after_expr
with Right_parenthesis :: tokens_after_rparen ->
 ( Parenthesized_Expr_as_Factor  expr_parse ,
   tokens_after_rparen)
```



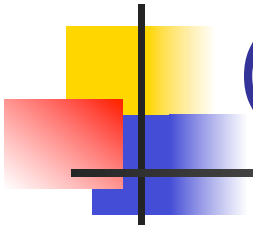
Error Cases

- What if no matching right parenthesis?

```
 | _ -> raise (Failure "No matching
rparen") ))
```

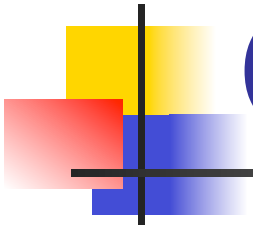
- What if no leading id or left parenthesis?

```
| _ -> raise (Failure "No id or lparen" ));;
```



(a + b) * c - d

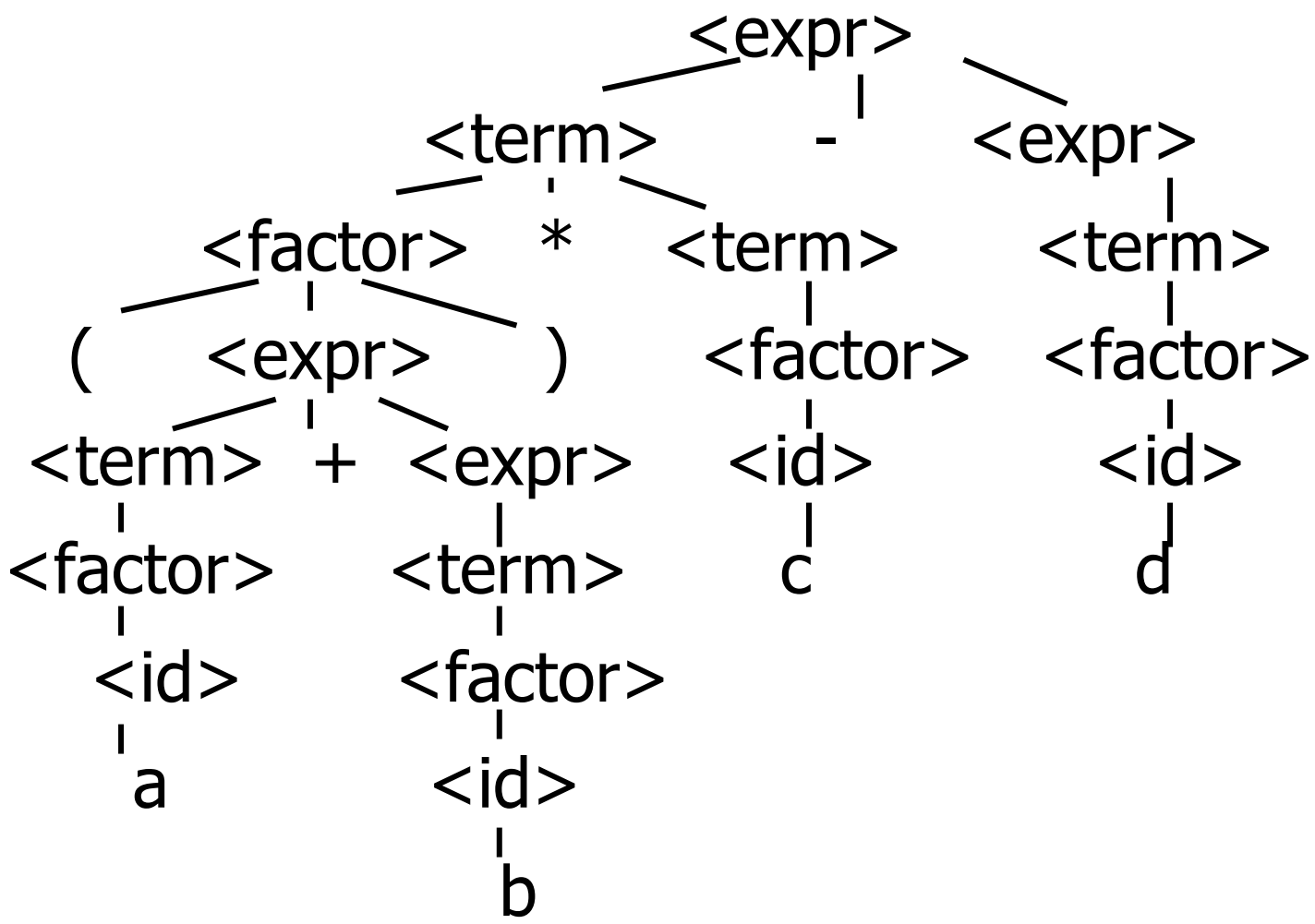
```
expr [Left_parenthesis; Id_token "a”;
  Plus_token; Id_token "b”;
  Right_parenthesis; Times_token;
  Id_token "c”; Minus_token;
  Id_token "d"];;
```

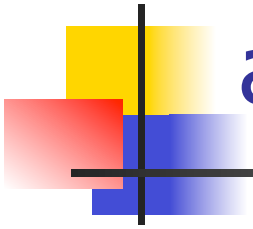


(a + b) * c - d

```
- : expr * token list =
(Minus_Expr
  (Mult_Term
    (Parenthesized_Expr_as_Factor
      (Plus_Expr
        (Factor_as_Term (Id_as_Factor "a"),
         Term_as_Expr (Factor_as_Term
   (Id_as_Factor "b")))),
     Factor_as_Term (Id_as_Factor "c")),
   Term_as_Expr (Factor_as_Term (Id_as_Factor
   "d"))),
 [])
```

(a + b) * c – d

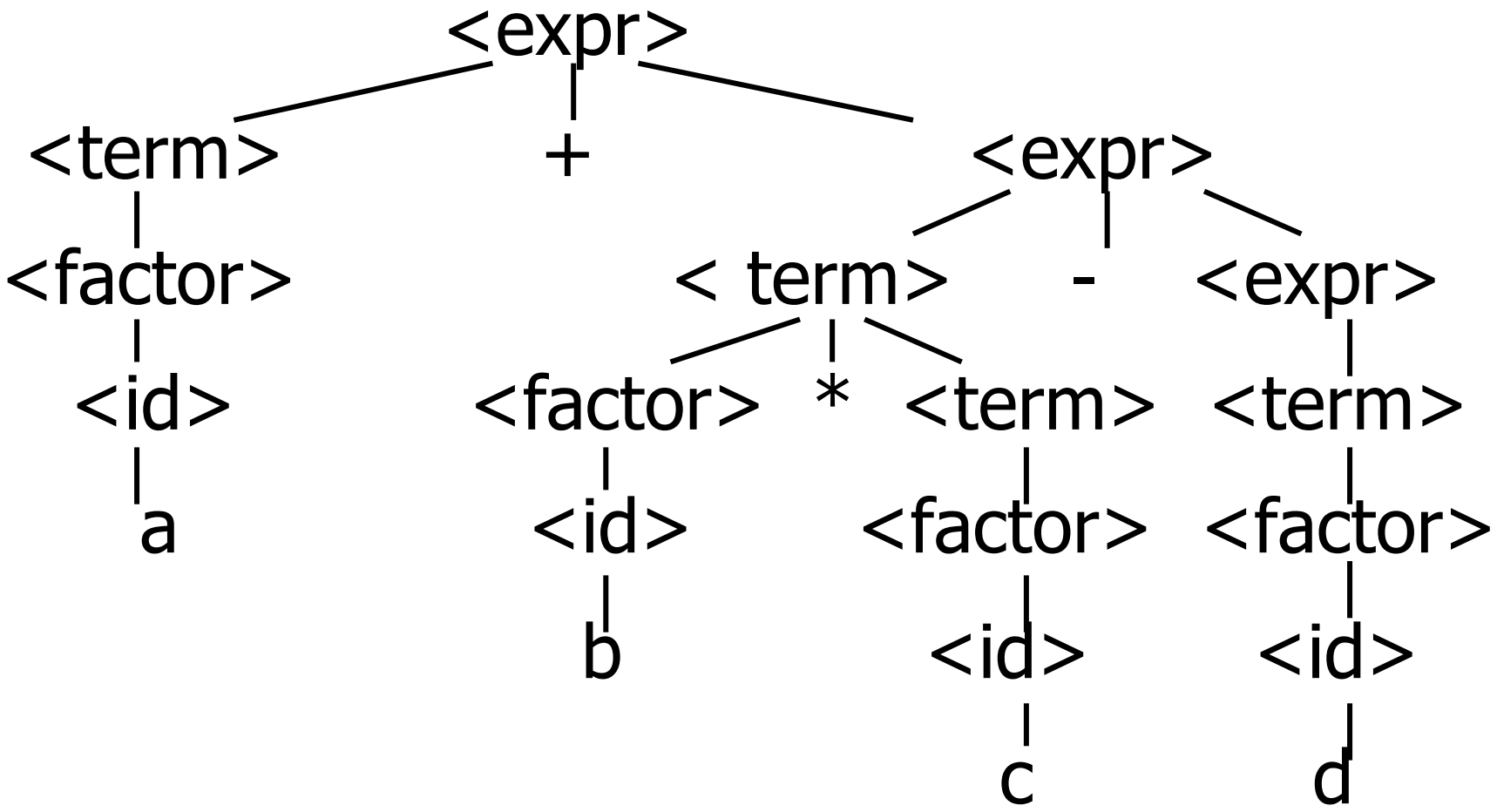

<expr>
<term>
-
<expr>
<factor>
*
<term>
<term>
(
<expr>
)
<factor>
<factor>
<term>
+
<expr>
<id>
<id>
<factor>
<term>
c
d
<id>
<factor>
a
<id>
b

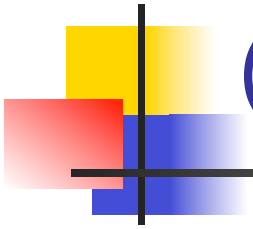


a + b * c – d

```
# expr [Id_token "a”; Plus_token; Id_token "b”;
   Times_token; Id_token "c”; Minus_token;
        Id_token "d"];;
- : expr * token list =
(Plus_Expr
  (Factor_as_Term (Id_as_Factor "a"),
   Minus_Expr
    (Mult_Term (Id_as_Factor "b", Factor_as_Term
   (Id_as_Factor "c")),
     Term_as_Expr (Factor_as_Term (Id_as_Factor
   "d")))),
 [])
```

a + b * c – d

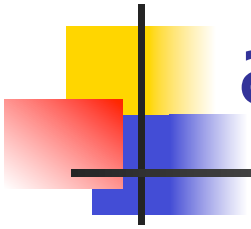

<expr>
<term>
+
<expr>
<factor>
< term>
-
<expr>
<id>
<factor>
*
<term>
<term>
a
<id>
<factor>
<factor>
b
<id>
<id>
c
d



(a + b * c - d

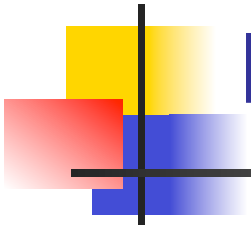
```
# expr [Left_parenthesis; Id_token "a”;
Plus_token; Id_token "b”; Times_token;
Id_token "c”; Minus_token; Id_token "d"];;

Exception: Failure "No matching rparen".
```

Can’t parse because it was expecting a right parenthesis but it got to the end without finding one



a + b) * c – d (

```
expr [Id_token "a”; Plus_token; Id_token "b”;
   Right_parenthesis; Times_token; Id_token "c”;
   Minus_token; Id_token "d”; Left_parenthesis];;
- : expr * token list =
(Plus_Expr
  (Factor_as_Term (Id_as_Factor "a"),
   Term_as_Expr (Factor_as_Term (Id_as_Factor
   "b"))),
 [Right_parenthesis; Times_token; Id_token "c";
   Minus_token; Id_token "d"; Left_parenthesis])
```

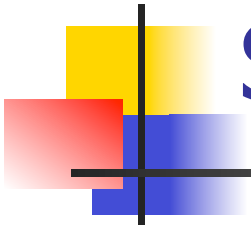


Parsing Whole String

- Q: How to guarantee whole string parses?
- A: Check returned tokens empty

```
let parse tokens  =
    match expr tokens
     with (expr_parse, []) -> expr_parse
     | _ -> raise (Failure “No parse");;
```

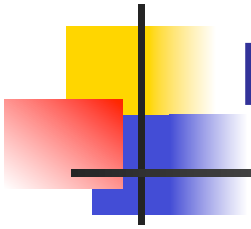
- Fixes <expr> as start symbol



Streams in Place of Lists

- More realistically, we don't want to create the entire list of tokens before we can start parsing
- We want to generate one token at a time and use it to make one step in parsing
- Can use (token * (unit -> token)) or (token * (unit -> token option))

  in place of token list



Problems for Recursive-Descent Parsing

- Left Recursion:

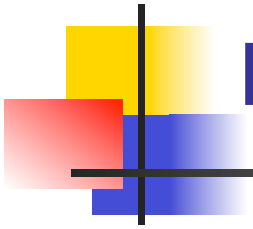
  A ::= Aw

  translates to a subroutine that loops forever
- Indirect Left Recursion:

  A ::= Bw

  B ::= Av

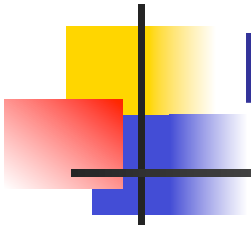
  causes the same problem



Problems for Recursive-Descent Parsing

- Parser must always be able to choose the next action based only only the very next token

- Pairwise Disjointedness Test: Can we always determine which rule (in the non-extended BNF) to choose based on just the first token



Pairwise Disjointedness Test

- For each rule

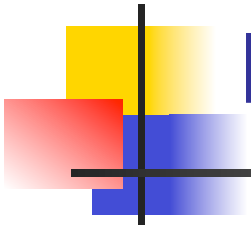
  A ::= *y*

  Calculate

  FIRST (*y*) =

  {a | *y* =>* a*w*} ∪ {ε | if y =>* ε}

- For each pair of rules A ::= *y* and A ::= *z*, require FIRST(*y*) ∩ FIRST(*z*) = { }



Example

Grammar:

<S> ::= <A> a <B> b

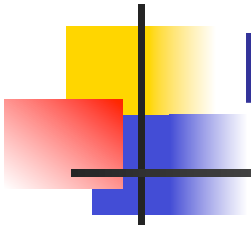
<A> ::= <A> b | b

<B> ::= a <B> | a

FIRST (<A> b) = {b}

FIRST (b) = {b}

Rules for <A> not pairwise disjoint



Eliminating Left Recursion

- Rewrite grammar to shift left recursion to right recursion
  - Changes associativity
- Given

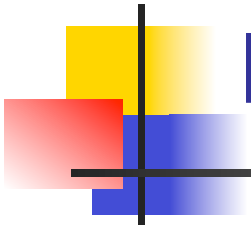
<expr> ::= <expr> + <term> and

<expr> ::= <term>

- Add new non-terminal <e> and replace above rules with

<expr> ::= <term><e>

<e> ::= + <term><e> | ε



Factoring Grammar

- Test too strong: Can't handle

  <expr> ::= <term> [(+ | -) <expr>]

- Answer: Add new non-terminal and replace above rules by

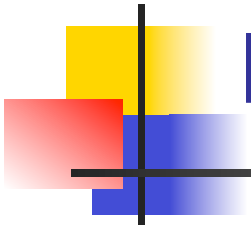
  <expr> ::= <term><e>

  <e> ::= + <term><e>

  <e> ::= - <term><e>

  <e> ::= ε

- You are delaying the decision point



Example

Both <A> and <B> have problems:

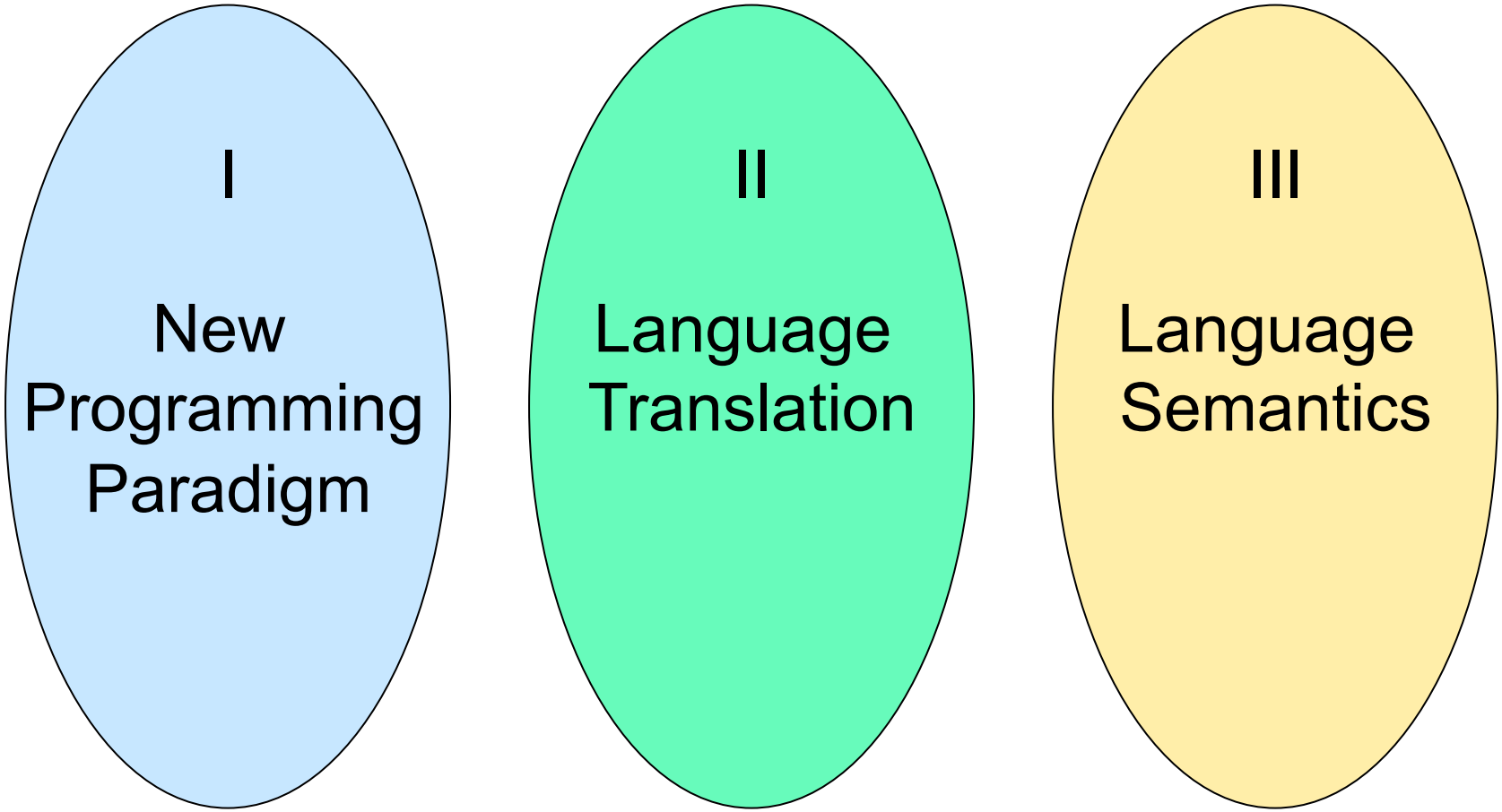
<S> ::= <A> a <B> b
<A> ::= <A> b | b
<B> ::= a <B> | a

Transform grammar to:

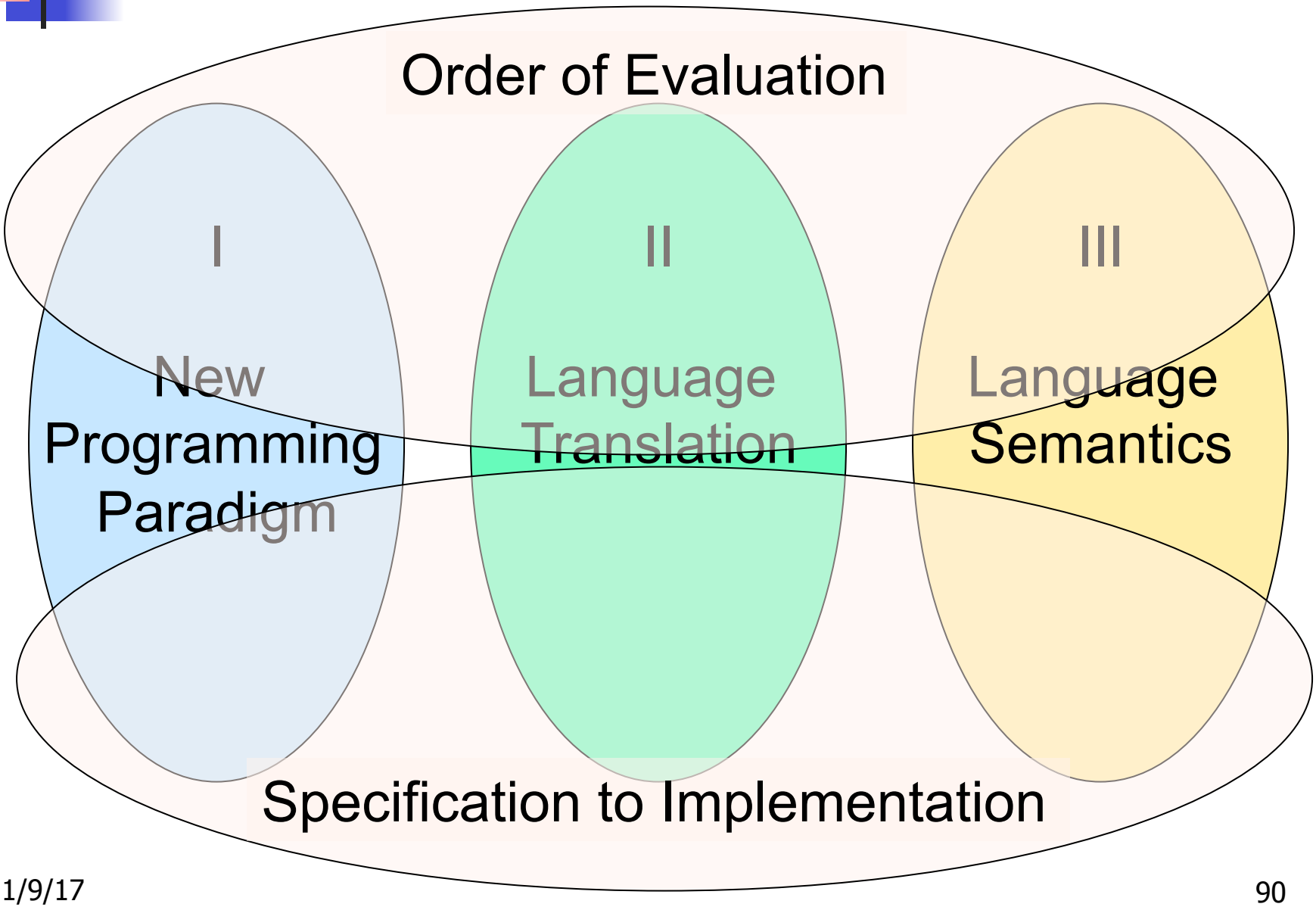
<S> ::= <A> a <B> b
<A> ::-= b<A1>
<A1> :: b<A1> | ε
<B> ::= a<B1>
<B1> ::= a<B1> | ε

Programming Languages & Compilers

Three Main Topics of the Course

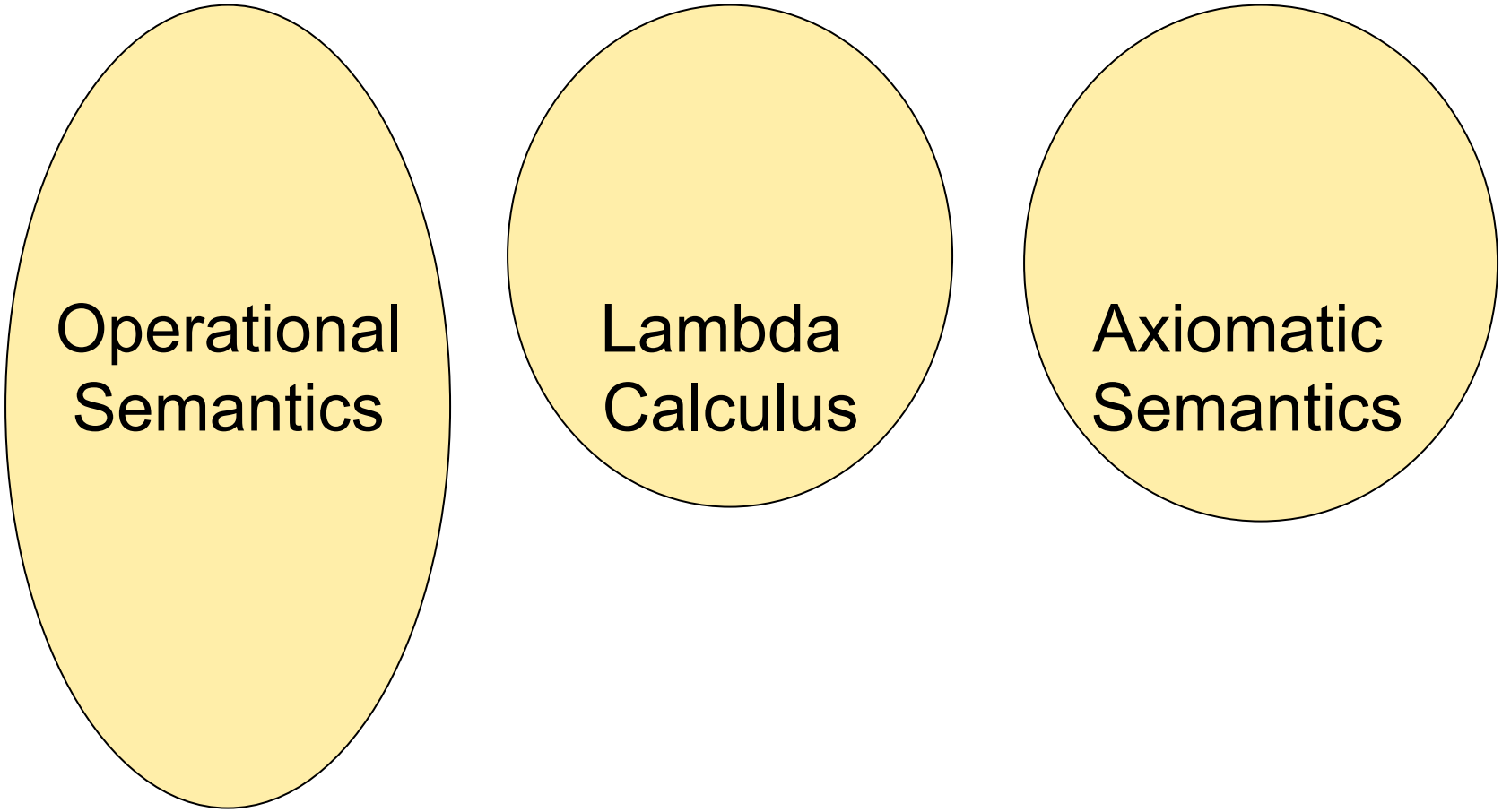


Programming Languages & Compilers

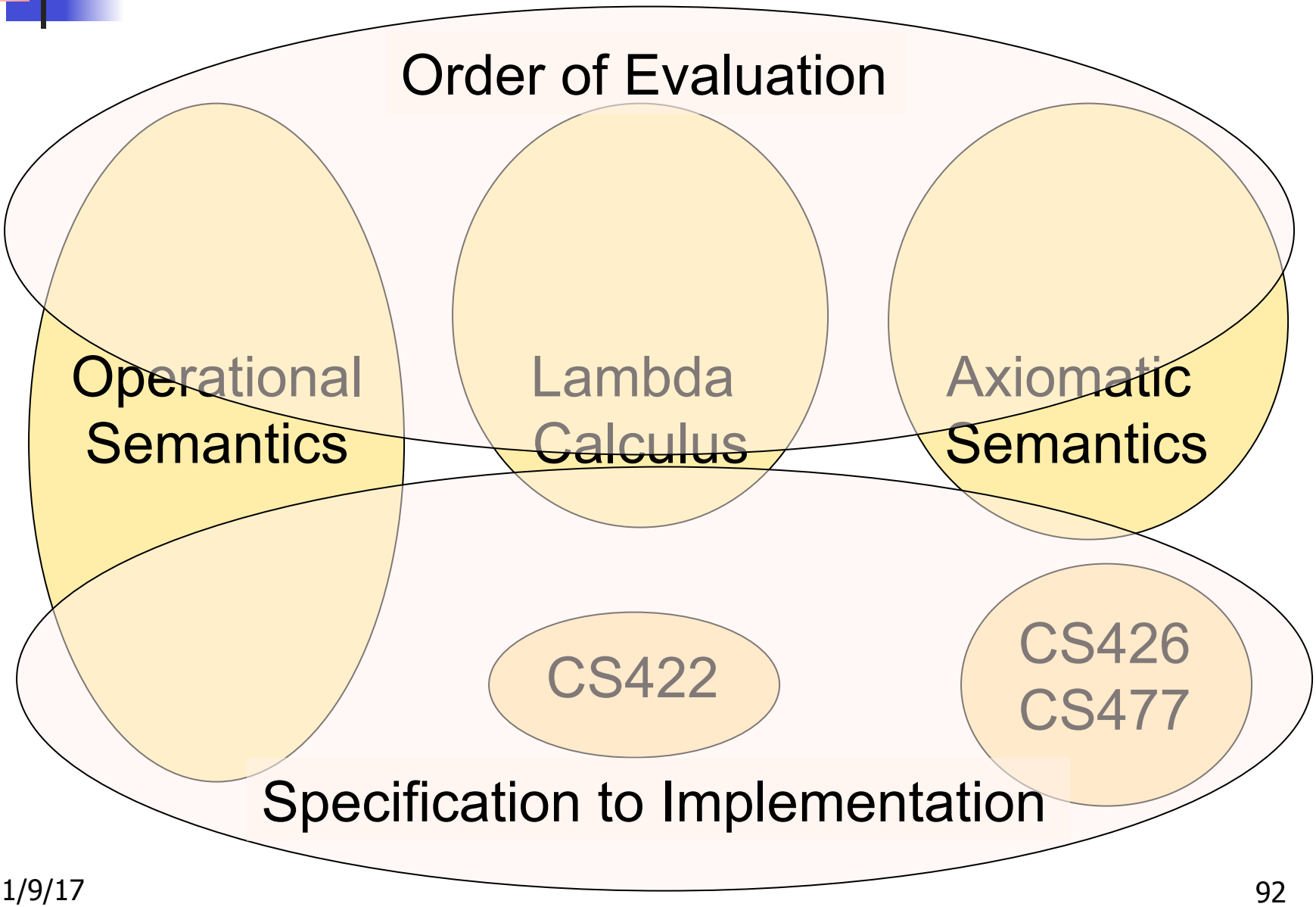


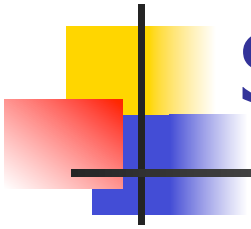
Programming Languages & Compilers

III : Language Semantics



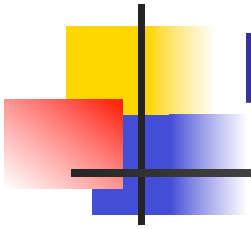
Programming Languages & Compilers





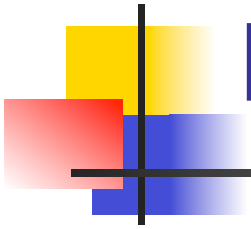
Semantics

- Expresses the meaning of syntax
- Static semantics
  - Meaning based only on the form of the expression without executing it
  - Usually restricted to type checking / type inference



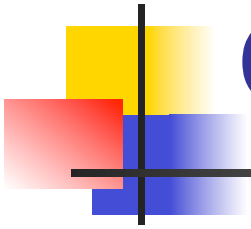
Dynamic semantics

- Method of describing meaning of executing a program
- Several different types:
  - Operational Semantics
  - Axiomatic Semantics
  - Denotational Semantics



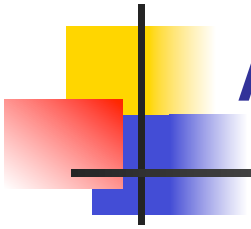
Dynamic Semantics

- Different languages better suited to different types of semantics
- Different types of semantics serve different purposes



Operational Semantics

- Start with a simple notion of machine
- Describe how to execute (implement) programs of language on virtual machine, by describing how to execute each program statement (ie, following the *structure* of the program)
- Meaning of program is how its execution changes the state of the machine
- Useful as basis for implementations



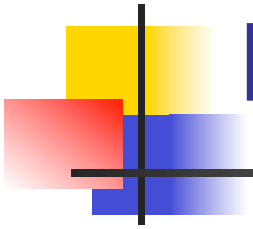
Axiomatic Semantics

- Also called Floyd-Hoare Logic
- Based on formal logic (first order predicate calculus)
- Axiomatic Semantics is a logical system built from *axioms* and *inference rules*
- Mainly suited to simple imperative programming languages

Axiomatic Semantics

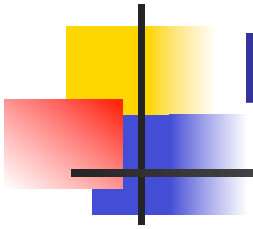
- Used to formally prove a property (*post-condition*) of the *state* (the values of the program variables) after the execution of program, assuming another property (*pre-condition*) of the state before execution
- Written :

  {Precondition} Program {Postcondition}
- Source of idea of *loop invariant*



Denotational Semantics

- Construct a function $\mathcal{M}$ assigning a mathematical meaning to each program construct
- Lambda calculus often used as the range of the meaning function
- Meaning function is compositional: meaning of construct built from meaning of parts
- Useful for proving properties of programs



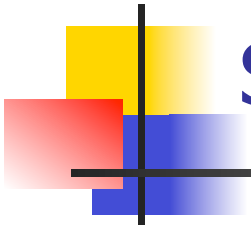
Natural Semantics

- Aka Structural Operational Semantics, aka "Big Step Semantics"
- Provide value for a program by rules and derivations, similar to type derivations
- Rule conclusions look like

$$(C, m) \Downarrow m'$$

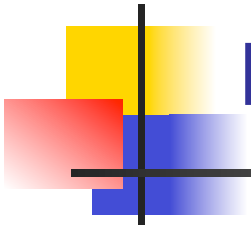
or

$$(E, m) \Downarrow v$$



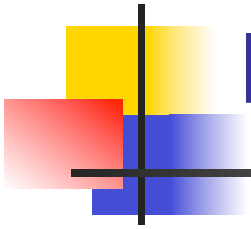
Simple Imperative Programming Language

- $I \in Identifiers$
- $N \in Numerals$
- B ::= true | false | B & B | B or B | not B | $E < E$ | $E = E$
- E::= N | I | $E + E$ | $E * E$ | $E - E$ | $- E$
- C::= skip | $C;C$ | I ::= E | if B then C else C fi | while B do C od



Natural Semantics of Atomic Expressions

- Identifiers: $(I,m) \Downarrow m(I)$
- Numerals are values: $(N,m) \Downarrow N$
- Booleans: (true,*m*) ⇓ true
  (false ,*m*) ⇓ false

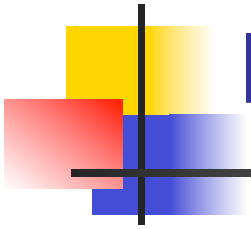


Booleans:

$$\frac{(B, m) \Downarrow \text{false}}{(B \,\&\, B', m) \Downarrow \text{false}} \qquad \frac{(B, m) \Downarrow \text{true} \quad (B', m) \Downarrow b}{(B \,\&\, B', m) \Downarrow b}$$

$$\frac{(B, m) \Downarrow \text{true}}{(B \text{ or } B', m) \Downarrow \text{true}} \qquad \frac{(B, m) \Downarrow \text{false} \quad (B', m) \Downarrow b}{(B \text{ or } B', m) \Downarrow b}$$

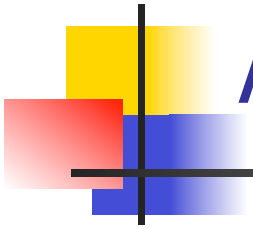
$$\frac{(B, m) \Downarrow \text{true}}{(\text{not } B, m) \Downarrow \text{false}} \qquad \frac{(B, m) \Downarrow \text{false}}{(\text{not } B, m) \Downarrow \text{true}}$$



Relations

$$\frac{(E, m) \Downarrow U \quad (E', m) \Downarrow V \quad U \sim V = b}{(E \sim E', m) \Downarrow b}$$

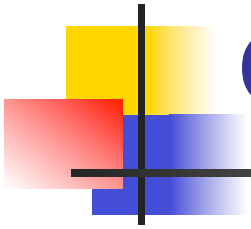
- By $U \sim V = b$, we mean does (the meaning of) the relation $\sim$ hold on the meaning of U and V
- May be specified by a mathematical expression/equation or rules matching U and V



Arithmetic Expressions

$$\frac{(E, m) \Downarrow U \quad (E', m) \Downarrow V \quad U \; op \; V = N}{(E \; op \; E', m) \Downarrow N}$$

where N is the specified value for $U \; op \; V$

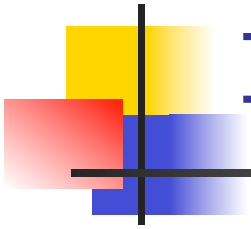


Commands

Skip: $(\text{skip}, m) \Downarrow m$

Assignment:
$$\frac{(E,m) \Downarrow V}{(I ::= E, m) \Downarrow m[I \text{ <-- } V]}$$

Sequencing:
$$\frac{(C,m) \Downarrow m' \quad (C',m') \Downarrow m''}{(C;C', m) \Downarrow m''}$$



If Then Else Command

$$\frac{(B,m) \Downarrow \text{true} \quad (C,m) \Downarrow m'}{(\text{if } B \text{ then } C \text{ else } C' \text{ fi}, m) \Downarrow m'}$$

$$\frac{(B,m) \Downarrow \text{false} \quad (C',m) \Downarrow m'}{(\text{if } B \text{ then } C \text{ else } C' \text{ fi}, m) \Downarrow m'}$$

While Command

$$\frac{(B,m) \Downarrow \text{false}}{(\text{while } B \text{ do } C \text{ od}, m) \Downarrow m}$$

$$\frac{(B,m) \Downarrow \text{true} \quad (C,m) \Downarrow m' \quad (\text{while } B \text{ do } C \text{ od}, m') \Downarrow m''}{(\text{while } B \text{ do C od}, m) \Downarrow m''}$$

Example: If Then Else Rule

(if x > 5 then y:= 2 + 3 else y:=3 + 4 fi,
{x -> 7}) ⇓ ?

Example: If Then Else Rule

$$\frac{(x > 5, \{x \to 7\}) \Downarrow ?}{(\text{if } x > 5 \text{ then } y := 2 + 3 \text{ else } y := 3 + 4 \text{ fi}, \{x \to 7\}) \Downarrow \ ?}$$

Example: Arith Relation

$$\dfrac{\dfrac{\dfrac{}{? > ? = ?}}{(x,\{x\text{->}7\})\Downarrow?} \quad \dfrac{}{(5,\{x\text{->}7\})\Downarrow?}}{(x > 5, \{x \text{->} 7\})\Downarrow?}$$

$$\dfrac{}{(\text{if } x > 5 \text{ then } y := 2 + 3 \text{ else } y := 3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow ?}$$

Example: Identifier(s)

$$\frac{7 > 5 = \text{true} \qquad \underline{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5}}{\dfrac{(x > 5, \{x \text{ -> } 7\})\Downarrow ?}{(\text{if } x > 5 \text{ then } y := 2 + 3 \text{ else } y := 3 + 4 \text{ fi}, \{x \text{ -> } 7\}) \Downarrow ?}}$$

Example: Arith Relation

$$\dfrac{\dfrac{7 > 5 = \text{true}}{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5}}{\dfrac{(x > 5, \{x \text{ -> } 7\})\Downarrow \text{true}}{(\text{if } x > 5 \text{ then } y := 2 + 3 \text{ else } y := 3 + 4 \text{ fi}, \{x \text{ -> } 7\}) \Downarrow ?}}$$

Example: If Then Else Rule

$$\dfrac{\dfrac{7 > 5 = \text{true}}{(x,\{x\text{->}7\}) \Downarrow 7 \quad (5,\{x\text{->}7\}) \Downarrow 5} \qquad (y{:=}\ 2 + 3, \{x\text{->}\ 7\} \Downarrow\ ?\ .}{(x > 5, \{x \text{->} 7\}) \Downarrow \text{true}}}{(\text{if } x > 5 \text{ then } y{:=}\ 2 + 3 \text{ else } y{:=}3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow\ ?}$$

Example: Assignment

$$\dfrac{\dfrac{7 > 5 = \text{true} \qquad \dfrac{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5}{(x > 5, \{x \text{ -> } 7\})\Downarrow \text{true}} \qquad \dfrac{(2+3, \{x\text{->}7\})\Downarrow ?}{(y\text{:= } 2 + 3, \{x\text{-> } 7\} \Downarrow ?}}{(\text{if } x > 5 \text{ then } y\text{:= } 2 + 3 \text{ else } y\text{:=}3 + 4 \text{ fi}, \{x \text{ -> } 7\}) \Downarrow ?}$$

Example: Arith Op

$$\dfrac{\dfrac{\dfrac{}{(x,\{x\text{->}7\})\Downarrow 7} \quad \dfrac{}{(5,\{x\text{->}7\})\Downarrow 5}}{(x > 5, \{x \text{->} 7\})\Downarrow \text{true}} \quad \dfrac{\dfrac{\dfrac{}{? + ? = ?}}{(2,\{x\text{->}7\})\Downarrow ? \quad (3,\{x\text{->}7\}) \Downarrow ?}}{(2+3, \{x\text{->}7\})\Downarrow ?}}{(y\text{:=}\ 2 + 3, \{x\text{->}\ 7\} \Downarrow ?}\ .$$

$$(\text{if } x > 5 \text{ then } y\text{:=}\ 2 + 3 \text{ else } y\text{:=}3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow ?$$

Example: Numerals

$$\dfrac{\dfrac{7 > 5 = \text{true}}{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5} \qquad \dfrac{2 + 3 = 5}{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\}) \Downarrow 3}}{\dfrac{(x > 5, \{x \text{->} 7\})\Downarrow \text{true} \qquad \dfrac{(2+3, \{x\text{->}7\})\Downarrow ?}{(y\text{:=} 2 + 3, \{x\text{->} 7\} \Downarrow ?}}{(\text{if } x > 5 \text{ then } y\text{:=} 2 + 3 \text{ else } y\text{:=}3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow ?}$$

Example: Arith Op

$$\dfrac{\dfrac{7 > 5 = \text{true}}{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5} \qquad \dfrac{2 + 3 = 5}{\dfrac{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\})\Downarrow 3}{(2+3,\ \{x\text{->}7\})\Downarrow 5}}}{\dfrac{(x > 5,\ \{x \text{->} 7\})\Downarrow \text{true} \qquad (y\text{:=}\ 2 + 3,\ \{x\text{->}\ 7\} \Downarrow ?}{(\text{if } x > 5 \text{ then } y\text{:=}\ 2 + 3 \text{ else } y\text{:=}3 + 4 \text{ fi},\ \{x \text{->} 7\}) \Downarrow\ ?}}$$

Example: Assignment

$$\dfrac{\dfrac{\dfrac{}{7 > 5 = \text{true}}}{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5} \qquad \dfrac{\dfrac{\dfrac{}{2 + 3 = 5}}{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\}) \Downarrow 3}}{(2+3, \{x\text{->}7\})\Downarrow 5}}{(x > 5, \{x \text{->} 7\})\Downarrow \text{true} \qquad (y\text{:=}\ 2 + 3, \{x\text{->}\ 7\} \Downarrow \{x\text{->}7, y\text{->}5\}}$$

$$(\text{if } x > 5 \text{ then } y\text{:=}\ 2 + 3 \text{ else } y\text{:=}3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow ?$$

Example: If Then Else Rule

$$\dfrac{\dfrac{7 > 5 = \text{true}}{(x,\{x\text{->}7\})\Downarrow 7 \quad (5,\{x\text{->}7\})\Downarrow 5} \qquad \dfrac{\dfrac{2 + 3 = 5}{(2,\{x\text{->}7\})\Downarrow 2 \quad (3,\{x\text{->}7\}) \Downarrow 3}}{(2+3, \{x\text{->}7\})\Downarrow 5}}{\dfrac{(x > 5, \{x \text{->} 7\})\Downarrow \text{true} \qquad (y\text{:=} 2 + 3, \{x\text{->} 7\} \Downarrow \{x\text{->}7, y\text{->}5\}}{(\text{if } x > 5 \text{ then } y\text{:=} 2 + 3 \text{ else } y\text{:=}3 + 4 \text{ fi}, \{x \text{->} 7\}) \Downarrow \{x\text{->}7, y\text{->}5\}}}$$

Let in Command

$$\frac{(E,m) \Downarrow v \quad (C,m[I<\text{-}v]) \Downarrow m'}{(\text{let } I = E \text{ in } C,\ m) \Downarrow m''}$$

Where $m''(y) = m'(y)$ for $y \neq I$ and $m''(I) = m(I)$ if $m(I)$ is defined, and $m''(I)$ is undefined otherwise

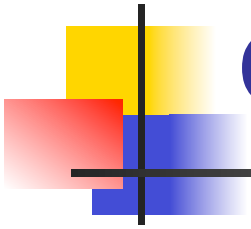
Example

$$\dfrac{\dfrac{(x,\{x\text{->}5\}) \Downarrow 5 \quad (3,\{x\text{->}5\}) \Downarrow 3}{(x+3,\{x\text{->}5\}) \Downarrow 8} \quad (5,\{x\text{->}17\}) \Downarrow 5 \qquad (x:=x+3,\{x\text{->}5\}) \Downarrow \{x\text{->}8\}}{(\text{let } x = 5 \text{ in } (x:=x+3), \{x \text{ -> } 17\}) \Downarrow ?}$$

Example

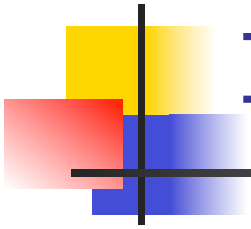
$$\dfrac{(5,\{x\text{->}17\}) \Downarrow 5 \qquad \dfrac{(x,\{x\text{->}5\}) \Downarrow 5 \quad (3,\{x\text{->}5\}) \Downarrow 3}{(x+3,\{x\text{->}5\}) \Downarrow 8}}{(x\text{:=}x+3,\{x\text{->}5\}) \Downarrow \{x\text{->}8\}}$$

$$(\text{let } x = 5 \text{ in } (x\text{:=}x+3), \{x \text{ -> } 17\}) \Downarrow \{x\text{->}17\}$$



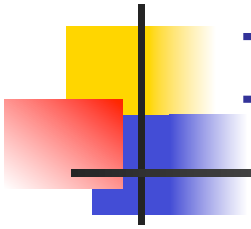
Comment

- Simple Imperative Programming Language introduces variables *implicitly* through assignment
- The let-in command introduces scoped variables *explictly*
- Clash of constructs apparent in awkward semantics



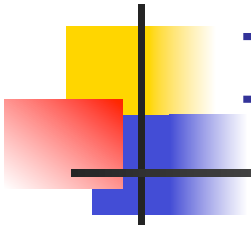
Interpretation Versus Compilation

- A **compiler** from language L1 to language L2 is a program that takes an L1 program and for each piece of code in L1 generates a piece of code in L2 of same meaning
- An **interpreter** of L1 in L2 is an L2 program that executes the meaning of a given L1 program
- Compiler would examine the body of a loop once; an interpreter would examine it every time the loop was executed



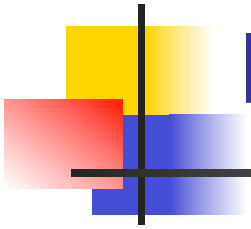
Interpreter

- An *Interpreter* represents the operational semantics of a language L1 (source language) in the language of implementation L2 (target language)
- Built incrementally
  - Start with literals
  - Variables
  - Primitive operations
  - Evaluation of expressions
  - Evaluation of commands/declarations



Interpreter

- Takes abstract syntax trees as input
  - In simple cases could be just strings
- One procedure for each syntactic category (nonterminal)
  - eg one for expressions, another for commands
- If Natural semantics used, tells how to compute final value from code
- If Transition semantics used, tells how to compute next “state”
  - To get final value, put in a loop



Natural Semantics Example

- compute_exp (Var(v), m) = look_up v m
- compute_exp (Int(n), _) = Num (n)
- …
- compute_com(IfExp(b,c1,c2),m) =

  if compute_exp (b,m) = Bool(true)

  then compute_com (c1,m)

  else compute_com (c2,m)

Natural Semantics Example

- compute_com(While(b,c), m) =
  if compute_exp (b,m) = Bool(false)
  then m
  else compute_com
  (While(b,c), compute_com(c,m))

- May fail to terminate - exceed stack limits
- Returns no useful information then