Compiler Design

Lecture 7: Parse Tree and Abstract Syntax

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A parser does more than simply recognising syntax. It performs certains actions such as:

- evaluate code (interpreter)
- emit code (simple compiler)
- build an internal representation of the program (multi-pass compiler)

In the case of

- a hand-written recursive descent parser:
  integrate the actions with the parsing functions
- an automatically generated parser:
  add actions to the grammar

Syntax Tree

In a multi-pass compiler, the parser builds a syntax tree which is used by the subsequent passes.

A syntax tree can be:

- a concrete syntax tree, or parse tree, if it directly corresponds to the context-free grammar
- an abstract syntax tree if it corresponds to a simplified — or abstract — grammar

The abstract syntax tree (AST) is usually used in compilers.

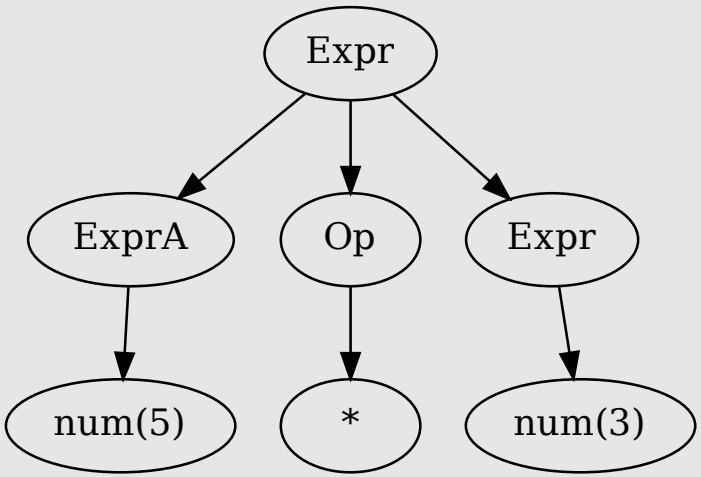
Table of contents

Parse Tree

Example: Concrete Syntax Tree (Parse Tree)

```
Expr ::= Expr Op Expr | num | id
Op   ::= + | *
```

Concrete Syntax Tree for $5 * 3$



Ambiguity definition

- If a grammar has more than one leftmost (or rightmost) derivations for a single sentential form, the grammar is ambiguous
- This is a problem when interpreting an input program or when building an internal representation

Parse Tree

Ambiguous Grammars: nesting of structures

Example: Dangling-Else

Ambiguous grammar

```
Stmt ::= if Expr then Stmt
       | if Expr then Stmt else Stmt
       | NonIfStmt
```

input

```
if E1 then if E2 then S1 else S2
```

One possible interpretation

```
if E1 then
  if E2 then
    S1
else
  S2
```

Another possible interpretation

```
if E1 then
  if E2 then
    S1
  else
    S2
```

Removing Ambiguity

Must rewrite the grammar to avoid generating the problem:

- By adding a keyword to "end" the `if`:
  - *e.g.* Bash: **if** … **fi**
  - *e.g.* Ada: **if** … **end if**;
- By forcing the programmer to align the `else`:
  - *e.g.* Python

```
if cond1:
    if cond2:
        ...
else:
    ...
```

- Or by keeping the same language syntax and add extra rules in the grammar to match, for instance, each else to innermost unmatched if (common sense).

Let's try to keep the same language syntax and modify the grammar.

Unambiguous grammar

```
Stmt      ::= if Expr then Stmt
            | if Expr then WithElse else Stmt
            | NonIfStmt
WithElse  ::= if Expr then WithElse else WithElse
            | NonIfStmt
```

- Intuition: the WithElse restricts what can appear in the then part
- With this grammar, the example has only one derivation

Unambiguous grammar for dangling-else

```
Stmt     ::= if Expr then Stmt
           | if Expr then WithElse else Stmt
           | NonIfStmt
WithElse ::= if Expr then WithElse else WithElse
           | NonIfStmt
```

Derivation for: if E1 then if E2 then S1 else S2

```
Stmt
if Expr then Stmt
if E1 then Stmt
if E1 then if Expr then WithElse else Stmt
if E1 then if E2 then WithElse else Stmt
if E1 then if E2 then S1 else Stmt
if E1 then if E2 then S1 else S2
```

This binds the else controlling S2 to the inner if.

Beware: Dangling-Else and Recursive Descent Parser

Unambiguous grammar for dangling-else

```
Stmt      ::= if Expr then Stmt
            | if Expr then WithElse else Stmt
            | NonIfStmt
WithElse  ::= if Expr then WithElse else WithElse
            | NonIfStmt
```

⚠ This grammar is not LL(k) ⚠

A recursive desent parser should use the original grammar:

Ambiguous grammar

```
Stmt ::= if Expr then Stmt [else Stmt]
       | NonIfStmt
```

This works because when the recursive desent parser parses an `if` statement, it will always consume as much of the input as possible.

Therefore, an **`else`** will always be associated with the nearest **`then`**.

Parse Tree

Ambiguous Grammars: operator precedence

Example : Arithmetic Operators

Ambiguous Grammar

```
Expr ::= Expr Op Expr | num | id
Op   ::= + | *
```

This grammar has multiple leftmost derivations for `x + 2 * y`

One possible derivation

```
Expr
Expr Op Expr
id(x) Op Expr
id(x) + Expr
id(x) + Expr Op Expr
id(x) + num(2) Op Expr
id(x) + num(2) * Expr
id(x) + num(2) * id(y)
```

`x + (2 * y)`

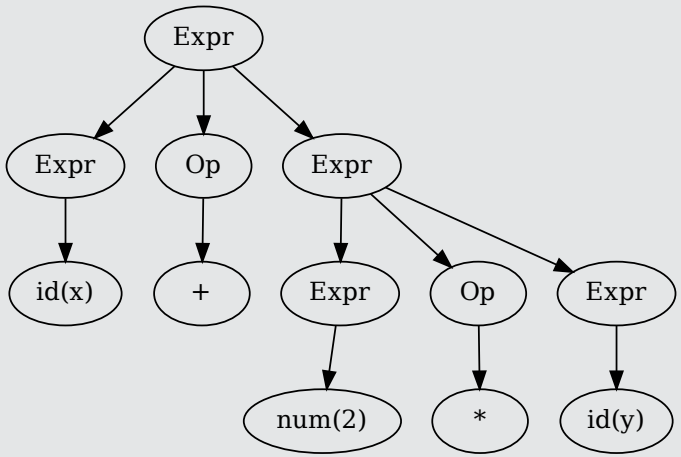
Another possible derivation

```
Expr
Expr Op Expr
Expr Op Expr Op Expr
id(x) Op Expr Op Expr
id(x) + Expr Op Expr
id(x) + num(2) Op Expr
id(x) + num(2) * Expr
id(x) + num(2) * id(y)
```

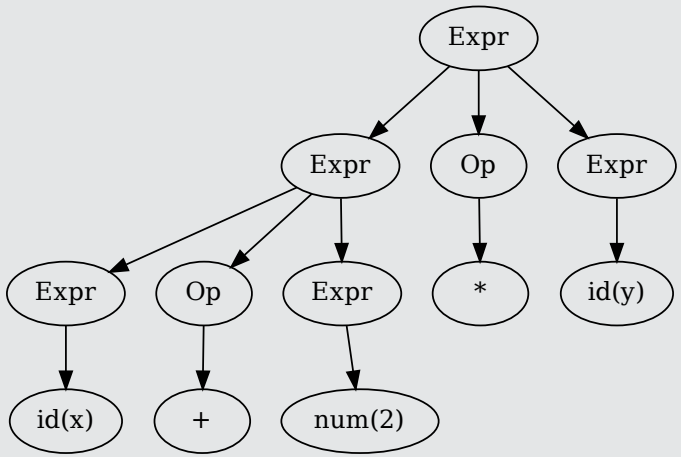
`(x + 2) * y`

Parse trees

$x + (2 * y)$



$(x + 2) * y$



Which one is correct?

As far as the grammar is concerned: both!

However, they represent different expressions!

Encoding Precedence

Some operators have higher precendence over others.

For instance, multiplication takes precendence over addition:

- $x + 2 * y = x + (2 * y)$
- $x * 2 + y = (x * 2) + y$

Grammar for basic arithmetic expressions

```
Expr ::= Expr Op Expr | num | id | '(' Expr ')'
Op   ::= '+' | '-' | '*' | '/'
```

Perhaps we can massage this grammar so that $+$ and $-$ have lower precendence than $*$ and $/$?

Grammar for basic arithmetic expressions

```
Expr ::= Expr Op Expr | num | id | '(' Expr ')'
Op   ::= '+' | '-' | '*' | '/'
```

Main idea: introduce one non-terminal symbol for every precedence level. One for $+$,$-$, and one for $*$ and $/$.

Grammar with precedence encoded

```
Expr   ::= Term ( ('+'| '-') Term )*
Term   ::= Factor ( ('*' | '/') Factor)*
Factor ::= number | id | '(' Expr ')'
```

Let's remove the EBNF syntax

Example: CFG for arithmetic expressions (EBNF form)

```
Expr   ::= Term ( ('+'| '-') Term )*
Term   ::= Factor ( ('*' | '/') Factor)*
Factor ::= number | id | '(' Expr ')'
```

After removal of EBNF syntax

```
Expr    ::= Term Terms
Terms   ::= ('+' | '-') Term Terms | ϵ
Term    ::= Factor Factors
Factors ::= ('*' | '/') Factor Factors | ϵ
Factor  ::= number | id | '(' Expr ')'
```

After further simplification

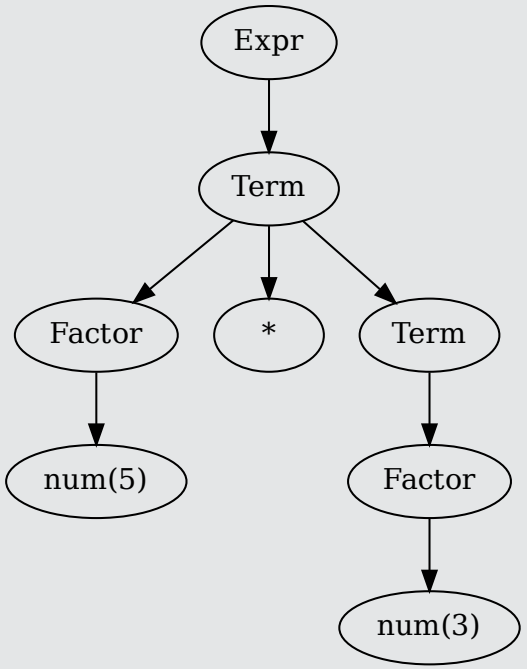
```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Concrete Syntax Tree (Parse Tree)

CFG for arithmetic expressions

```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Concrete Syntax Tree for $5 * 3$



Deeper ambiguity

- Ambiguity usually refers to confusion in the CFG (Context Free Grammar)
- Consider the following case: `a = f(17)`
  In some languages (*e.g.* Algol, Scala), `f` could be either a function of an array
- In such case, context is required
  - Need to track declarations
  - Really a type issue, not context-free syntax
  - Requires en extra-grammatical solution
  - Must handle these with a different mechanism

Solution:

Step outside the grammar rather than making it more complex.
This will be treated during semantic analysis.

Ambiguity Final Words

Ambiguity arises from two distinct sources:

- Confusion in the context-free syntax
  e.g. if then else
- Confusion that requires context to be resolved
  e.g. array vs function

Resolving ambiguity:

- To remove context-free ambiguity, rewrite the grammar
- To handle context-sensitive ambiguity delay the detection of such problem (semantic analysis phase)
  - For instance, it is legal during syntactic analysis to have:
    `void i; i=4;`

Abstract Syntax Tree

Abstract Syntax Tree

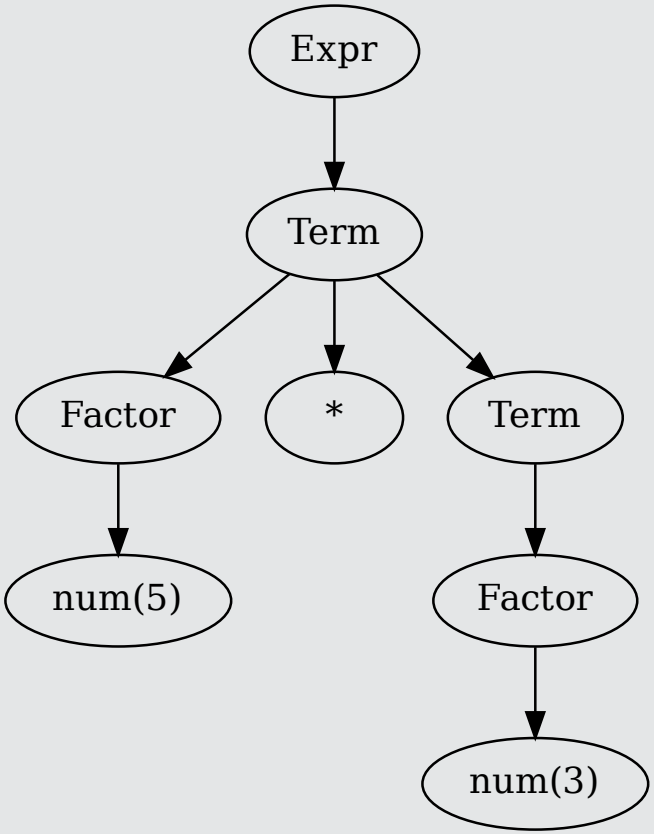
Abstract Syntax

Concrete Syntax Tree (Parse Tree)

CFG for arithmetic expressions

```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Concrete Syntax Tree for $5 * 3$



The concrete syntax tree contains a lot of unnecessary information.

It is possible to simplify the concrete syntax tree to remove the redundant information.

```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Exercise

1. Write the concrete syntax tree for $3 * (4 + 5)$
2. Simplify the tree.

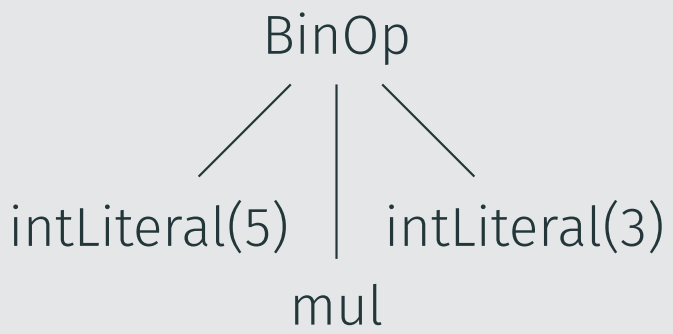
Abstract Grammar

These simplifications leads to a new simpler context-free grammar called Abstract Grammar.

Example: abstract grammar for arithmetic expressions

```
Expr  ::= BinOp | intLiteral | id
BinOp ::= Expr Op Expr
Op    ::= add | sub | mul | div
```

$5 * 3$



This is called an Abstract Syntax Tree

Example: abstract grammar for arithmetic expressions

```
Expr  ::= BinOp | intLiteral | id
BinOp ::= Expr Op Expr
Op    ::= add | sub | mul | div
```

Note that for given concrete grammar, there exist more than one abstract grammar. For instance:

```
Expr  ::= AddOp | SubOp | MulOp | DivOp | intLiteral | id
AddOp ::= Expr add Expr
SubOp ::= Expr sub Expr
MulOp ::= Expr mul Expr
DivOp ::= Expr div Expr
```

We pick the most suitable grammar for the compiler.

Abstract Syntax Tree

Abstract Syntax Tree Representation

Abstract Syntax Tree using Object Oriented Design

The Abstract Syntax Tree (AST) forms the main intermediate representation of the compiler's front-end.

$\forall$ non-terminal/terminal in the abstract grammar, define a class.

- If a non-terminal has any alternative on the rhs (right hand side), then the class is abstract (cannot instantiate it).
  The terminal or non-terminal appearing on the rhs are subclasses of the non-terminal on the lhs.
- The sub-trees are represented as fields in the class.
- Each non-abstract class has a unique constructor.
- If a terminal does not store any information, then we can use an Enum type in Java instead of a class.

Example: abstract grammar for arithmetic expressions

```
Expr  ::= BinOp | intLiteral | id
BinOp ::= Expr Op Expr
Op    ::= add | sub | mul | div
```

Corresponding Java Classes

```
abstract class Expr { }

class IntLiteral extends Expr {
  int i;
  IntLiteral(int i){...}
}

class Id extends Expr {
  String name;
  Id(String name){...}
}

class BinOp extends Expr {
  Op op;
  Expr lhs;
  Expr rhs;
  BinOp(Op op, Expr lhs, Expr rhs) {...}
}

enum Op {ADD, SUB, MUL, DIV}
```

Abstract Syntax Tree

AST Builder

CFG for arithmetic expressions

```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Current Parser (class)

```
void parseExpr() {
  parseTerm();
  if (accept(PLUS|MINUS))
    nextToken();
    parseExpr();
}

void parseTerm() {
  parseFactor();
  if (accept(TIMES|DIV))
    nextToken();
    parseTerm();
}
```

```
void parseFactor() {
  if (accept(LPAR))
    parseExpr();
    expect(RPAR);
  else
    expect(NUMBER|ID);
}
```

Building an AST

Let's modify our existing parser to produce the AST:

- Each parseXXX() function will now return an AST node.
- We assume that `expect` now returns the token.

Current Parser

```
void parseExpr() {
  parseTerm();
  if (accept(PLUS|MINUS))
    nextToken();
    parseExpr();
}
```

AST building (modified Parser)

```
Expr parseExpr() {
  Expr lhs = parseTerm();
  if (accept(PLUS|MINUS))
    Op op;
    if (token == PLUS)
      op = ADD;
    else // token == MINUS
      op = SUB;
    nextToken();
    Expr rhs = parseExpr();
    return new BinOp(op, lhs, rhs);
  return lhs;
}
```

Current Parser

```
void parseTerm() {
  parseFactor();
  if (accept(TIMES|DIV))
    nextToken();
    parseTerm();
}
```

AST building (modified Parser)

```
Expr parseTerm() {
  Expr lhs = parseFactor();
  if (accept(TIMES|DIV))
    Op op;
    if (token == TIMES)
      op = MUL;
    else // token == DIV
      op = DIV;
    nextToken();
    Expr rhs = parseTerm();
    return new BinOp(op, lhs, rhs);
  return lhs;
}
```

Current Parser

```
void parseFactor() {
  if (accept(LPAR))
    parseExpr();
    expect(RPAR);
  else
    expect(NUMBER|ID);
}
```

AST building (modified Parser)

```
Expr parseFactor() {
  if (accept(LPAR))
    Expr e = parseExpr();
    expect(RPAR);
    return e;
  else  if (accept(NUMBER))
    IntLiteral il = parseNumber();
    return il;
  else
    Id id = parseIdent();
    return id;
}


IntLiteral parseNumber() {
  Token n = expect(NUMBER);
  int i = Integer.parseInt(n.data);
  return new IntLiteral(i);
}

Id parseId() {
  Token t = expect(IDENT);
  return new Id(t.data);
}
```

Beware: Associativity

What is the result of $2 - 3 - 4$?

- -5

Why? Mathematical operators are usually left-associative:

- $2 - 3 - 4 = (2 - 3) - 4 = -1 - 4 = -5$

How does our parser handle 2 – 3 – 4 ?

Parser code (partial)

```
Expr parseExpr() {
  Expr lhs = parseTerm();
  if (accept(PLUS|MINUS))
    Op op;
    if (token == PLUS) op = ADD;
    else op = SUB;
    nextToken();
    Expr rhs = parseExpr();
    return new BinOp(op, lhs, rhs);
  return lhs;
}
Expr parseTerm() {
  Expr lhs = parseFactor();
  if (accept(TIMES|DIV))
    ...
  return lhs;
}
Expr parseFactor() {
  if (accept(LPAR)) ...
  else if (accept(NUMBER))
    IntLiteral il = parseNumber();
    return il;
  else ...
}
```

Exercise: draw the AST

⚠ The resulting tree is right-associative!

How to solve this associativity problem?

Three solutions:

- Build the AST, and then use a pass to change nodes order.
- Modify the grammar.
- Modify the parser to directly produce the correct AST.

Let's try to modify our grammar

Grammar with righ-associative operators

```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Equivalent grammar with righ-associative operators

```
Expr    ::= Term ('+' | '-') Expr | Term
Term    ::= Factor ('*'|'/') Term | Factor)
Factor  ::= number | id | '(' Expr ')'
```

Grammar with left-associative operators

```
Expr    ::= Expr ('+' | '-') Term | Term
Term    ::= Term ('*'|'/') Factor | Factor)
Factor  ::= number | id | '(' Expr ')'
```

Can you see the problem?

Making our parser left-associative

Right-associative

```
Expr parseExpr() {
  Expr lhs = parseTerm();
  if (accept(PLUS|MINUS))
    Op op;
    if (token == PLUS)
      op = ADD;
    else
      op = SUB;
    nextToken();
    Expr rhs = parseExpr();
    return new BinOp(op, lhs, rhs);
  return lhs;
}
...
```

Left-associative

```
Expr parseExpr() {
  Expr lhs = parseTerm();
  while (accept(PLUS|MINUS))
    Op op;
    if (token == PLUS)
      op = ADD;
    else
      op = SUB;
    nextToken();
    Expr rhs = parseTerm();
    lhs = new BinOp(op, lhs, rhs);
  return lhs;
}
...
```

Recursion replaced by iteration.

Why does it work?

Grammar implemented by the “right-associative” parser

```
Expr    ::= Term (('+' | '-') Expr | ϵ)
Term    ::= Factor (('*'|'/') Term | ϵ)
Factor  ::= number | id | '(' Expr ')'
```

Remember where we came from:

EBNF form

```
Expr   ::= Term ( ('+'| '-') Term )*
Term   ::= Factor ( ('*' | '/') Factor)*
Factor ::= number | id | '(' Expr ')'
```

Putting it all together

Steps to produce a parser that builds a correct AST:

1. Start with the grammar and encode precedence;
2. Remove any left-recursion if present;
3. Pay attention to associativity of operators
    - For left-associative operators, use Kleen-closure (EBNF), this will lead to a loop in the parser
    - For right-associative operators, remove any Kleen-closure
4. Write recursive descent parser following the grammar and ensure left-associative operators are handled properly.

Next lecture

- AST processing