Lecture 2: Abstract and Concrete Syntax

Programming Languages Course
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Book: 2.8.2, 4.1 - 4.3

The central role of abstract syntax

Although lexing is the first compiler phase, we don't start from it.

Instead, we start from the middle, abstract syntax, which is

- the goal of lexing + parsing
- the starting point of code generation
- the domain of type checking and many optimizations
- the hub between the front end and the back end

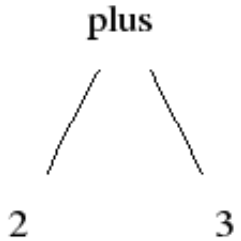
This lecture: how syntax rules look like.

Next lecture: how to write a grammar to generate a compiler front end.

Abstract and concrete syntax

Abstract syntax: what are the significant parts of the expression?

Example: a sum expression has its two operand expressions as its significant parts



Concrete syntaz: what does the expression look like?

Example: *the same* sum expression can look in different ways:

```
2 + 3                          -- infix

(+ 2 3)                        -- prefix

(2 3 +)                        -- postfix

bipush 2                       -- JVM
bipush 3
```

```
iadd

the sum of 2 and 3            -- English
```

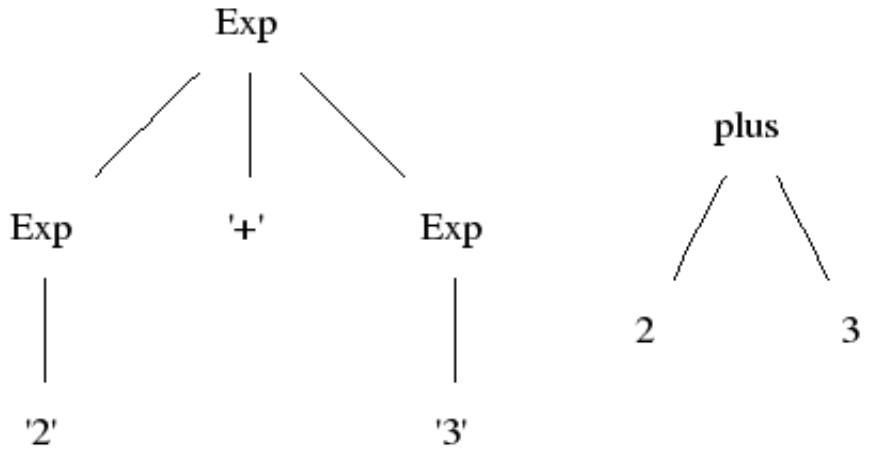
Parse trees and abstract syntax trees

Parse tree (left): show the concrete syntax (how tokens are grouped together)

- the tree initially constructed by the parser

Abstract tree (right): show the semantically significant structure

- the tree returned by the parser and manipulated by type checker



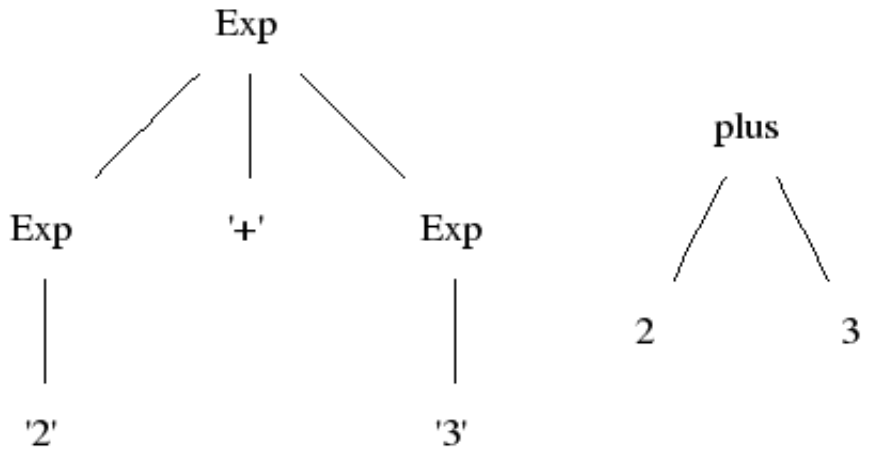
The structure of trees

Parse tree:

- nodes: **nonterminals** (= **syntactic categories**)
- leaves: **terminals** (= **tokens**)

Abstract tree:

- nodes: **constructor functions**
- leaves: atoms (= zero-place constructor functions)



The definition and construction of trees

Parse trees are defined by **context-free grammars**

```
Exp  ::= Exp  "+" Exp ;
Exp  ::= "2" ;
Exp  ::= "3" ;
```

Abstract trees are defined by **constructor type signatures**

```
plus : (Exp, Exp) -> Exp
2    : Exp
3    : Exp
```

From concrete to abstract syntax

1. Give a name (= label) to each rule:

```
Exp ::= Exp  "+" Exp        ==>    plus. Exp ::= Exp "+" Exp
```

2. Ignore terminals (= tokens, in quotes):

```
plus .Exp ::= Exp  "+" Exp  ==>    plus. Exp ::= Exp Exp
```

3. Treat label as constructor name, LHS (left-hand-side) as value type, RHS as argument types:

```
plus. Exp ::= Exp Exp       ==>    plus : (Exp, Exp) -> Exp
```

One abstract, many concrete

One abstract syntax tree can have infinitely many concrete syntax representations.

```
2 + 3                       -- infix

(+ 2 3)                     -- prefix
```

```
(2 3 +)                          -- postfix

bipush 2                         -- JVM
bipush 3
iadd

the sum of 2 and 3               -- English
```

Remember: terminals don't matter.

Separating abstract from concrete syntax

One could give a separate abstract syntax rule

```
fun plus : Exp -> Exp -> Exp
```

and functions computing the concrete syntax as **linearization**:

```
lin plus x y = x ++ "+" ++ y                    -- infix

lin plus x y = "(" ++ "+" ++ x ++ y ++ ")"      -- prefix

lin plus x y = "(" ++ x ++ y ++ "+" ++ ")"      -- postfix

lin plus x y = x ++ y ++ "iadd"                 -- JVM

lin plus x y = "the sum of" ++ x ++ "and" ++ y  -- English
```

This leads to more expressive grammars, definable in GF (Grammatical Framework).

(For fun) using GF

Concrete syntaxes can be different languages.

GF has tools for visualizing trees and word alignment:

tournesol.cs.chalmers.se:41296

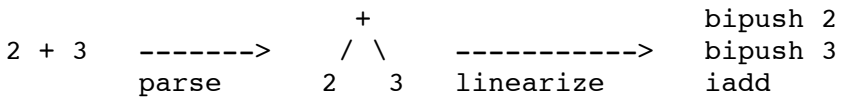
The fridge magnet interface:

tournesol.cs.chalmers.se:41296/fridge

The main idea of compilation

To compile:

- **parse** with the concrete syntax of source language
- **linearize** the resulting tree into the target language



This is the idea of **syntax-directed translation**.

Notice: from a grammar, both parsing and linearization are created automatically.

Algebraic datatypes

Abstract syntax can be expressed as **algebraic datatypes**.

They have a direct support in Haskell, as `data` types.

You just have to follow the syntax convetions: constructor begin with capital letters.

```
data Exp = Eplus Exp Exp
         | E2
         | E3
```

This is one reason why Haskell is so well suited for compiler construction.

But: we will show later how algebraic datatypes are encoded in Java.

Context-free grammars

Concrete syntax is described by **context-free grammars**.

Context-free grammar = **BNF grammar** (Backus-Naur form).

The mathematical definition is simple:

A context-free grammar is a quadruple (*T*,*N*,*S*,*R*) where

- *T* and *N* are disjoint sets, called **terminals** and **nonterminals**, respectively
- *S* is a nonterminal, the **start category**
- *R* is a finite set of **rules**
- a rule is a pair (*C*, *t_1*...*t_n*) where
    - *C* is a nonterminal
    - each *t_1* is a terminal or a nonterminal
    - n >= 0

Example (the one above):

- *T* = {"+", "2", "3"}
- *N* = {Exp}
- *S* = Exp
- *R* = ((Exp, Exp "+" Exp), (Exp, "2"), (Exp, "3"))

The BNF Converter

We will follow the notation of BNF Converter (= BNFC), where

- rules have the form `C ::= ... ;`

- terminals are quoted strings e.g. `"+"`
- nonterminals are unquoted identifiers e.g. `Exp`
- each rule is preceded by a label and a dot, e.g. `EPlus.`

From a BNF grammar, the program automatically generates

- abstract syntax definition
- parser
- linearizer
- lexer
- all this in C, C++, C#, Haskell, Java, OCaml

Today, we will look at how BNF grammars are written, independently of BNFC.

Abstract and concrete syntax of BNF

In a sense, the mathematical definition of BNF is its abstract syntax!

Concrete syntaxes vary: for instance, in linguistics, the common form is

```
Exp -> Exp + Exp
```

In Ansi C specification (Kernighan and Ritchie),

Exp: Exp + Exp

It is also common to group the rules with common LHS:

```
Exp ::= Exp "+" Exp | "2" | "3"
```

This is often called **extended BNF** (which also has other abbreviations).

Example: BNF in BNF

This is a subset of the full definition

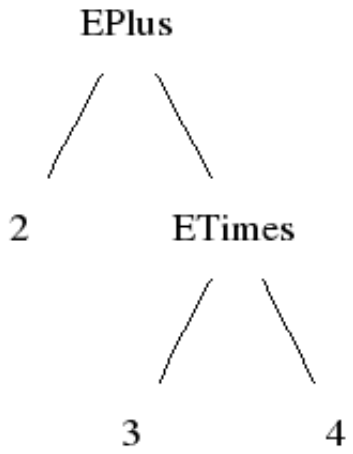
```
Gr.       Grammar  ::= ListRule ;
Rul.      Rule     ::= Ident "." Ident "::=" ListItem ;
ITerm.    Item     ::= String ;
INonterm. Item     ::= Ident ;

NilRule.  ListRule ::= ;
ConsRule. ListRule ::= Rule ";" ListRule ;

NilItem.  ListItem ::= ;
ConsItem. ListItem ::= Item ListItem ;
```

The grammar uses two primitive (i.e. internally defined) nonterminals:

- `String`: quoted string
- `Ident` : letter optionally followed by letters, digits, and `_ '`

Notations for abstract syntax trees

Graphically:



Haskell notation: label followed by subtrees, in parentheses if necessary:

```
EPlus 2 (ETimes 3 4)
```

Lisp notation: the same, but always in parentheses:

```
(EPlus 2 (ETimes 3 4))
```

(The original plan was to give Lisp a separate concrete syntax later!)

Writing a grammar: the main programming language structures

Usually it is good to proceed top-down: start from the largest program structures and proceed to the smallest.

In many languages, the levels are roughly:

- modules
- definitions
- statements
- expressions
- atoms

Functional languages skip the statement level.

Example: a simple imperative language

Each file contains a module, which is a sequence of function definitions.

A definition has a header and a sequence of statemens.

Statements are built from other statements and expressions.

Expressions are built from other expressions and atoms.

```
int plus (int x, int y)  // definition
{
  return x + y ;            // statement
}

int test()               // definition
{
  int x ;                   // statements
  x = readInt() ;
  int y ;
  y = readInt() ;
  return plus(x,y) ;
}
```

Rules for modules and function definitions

A module is a list of definitions

```
Mod.  Module ::= ListDef ;

NilDef.  ListDef ::= ;               -- empty list
ConsDef. ListDef ::= Def ListDef ;   -- add one more
```

A function definition has a header and a list of statements in curly brackets

```
Fun.  Def ::= Header "{" ListStm "}" ;

NilStm.  ListStm ::= ;
ConsStm. ListStm ::= Stm ";" ListStm ;
```

A header has a type, a name (an identifier), and a parameter declaration list

```
Head. Header ::= Type Ident "(" ListDecl ")" ;
```

Rule formats for sequences

Sequences of different kinds are very common.

BNFC has a special notation for list categories: `[C]`.

There is also a special notation for list rule ("Nil" and "Cons"):

```
terminator Stm ";" ;
```

abbreviates the two rules

```
NilStm.  ListStm ::= ;
ConsStm. ListStm ::= Stm ";" ListStm ;
```

It says: "statements in a statement list are terminated by a semicolon".

There is also the form

```
separator Decl "," ;
```

which says: "declarations in a declaration list are separated by a comma".

Rules for modules and function definitions: Version 2

A module is a list of definitions

```
Mod.  Module ::= [Def] ;

terminator Def "" ;

Fun.  Def    ::= Header "{" [Stm] "}" ;

terminator Stm ";" ;

Head. Header ::= Type Ident "(" [Decl] ")" ;
```

Rules for declarations, statements and expressions

A declaration has a type and an identifier:

```
DTyp.  Decl   ::= Type Ident ;
```

A statement is a declaration, an expression, or a return of an expression:

```
SDecl. Stm    ::= Decl ;
SExp.  Stm    ::= Exp ;
SRet.  Stm    ::= "return" Exp ;
```

An expression is an identifier, a function call, an assignment, or a sum:

```
EId.   Exp    ::= Ident ;
ECall. Exp    ::= Ident "(" [Exp] ")" ;
EAss.  Exp    ::= Ident "=" Exp ;
EPlus. Exp    ::= Exp "+" Exp ;
```

Expressions in a list are separated by commas:

```
separator Exp "," ;
```

Atoms

There is a type of integers:

```
TInt.  Type   ::= "int" ;
```

The category `Ident` is defined internally in BNFC, and needs hence no rule. (Actually, rules for internally defined categories are illegal.)

More on atoms in next week's lectures:

- other internally defined types
- how to define your own token types

The syntax tree of the example

```
Mod [
  Fun
    (Head
      TInt
      (Ident "plus")
      [DTyp TInt (Ident "x"), DTyp TInt (Ident "y")])
    [SRet (EPlus (EId (Ident "x")) (EId (Ident "y")))],
  Fun
    (Head
      TInt
      (Ident "test")
      [])
    [SDecl (DTyp TInt (Ident "x")),
     SExp (EAss (Ident "x") (ECall (Ident "readInt") [])),
     SDecl (DTyp TInt (Ident "y")),
     SExp (EAss (Ident "y") (ECall (Ident "readInt") [])),
     SRet (ECall (Ident "plus") [EId (Ident "x"),EId (Ident "y")])]]
```

Abstract syntax representation in Haskell

Each category is a datatype. Lists are represented as Haskell lists.

```
data Module =
   Mod [Def]

data Def =
   Fun Header [Stm]

data Header =
   Head Type Ident [Decl]

data Stm =
   SDecl Decl
 | SExp Exp
 | SRet Exp
```

Ident is also a datatype.

```
newtype Ident = Ident String
```

Syntax-directed translation is implemented as pattern matching (later lecture).

Abstract syntax representation in Java 1.5

Each category is an abstract class.

```
public abstract class Stm
public abstract class Exp
```

Each syntax constructor is a subclass of its value type class.

```
public class SDecl extends Stm {
  public final Decl decl_;
}
public class SExp extends Stm {
  public final Exp exp_;
}
public class EPlus extends Exp {
  public final Exp exp_1, exp_2;
}
```

Lists are treated using Java's linked lists.

```
public class ListDef extends java.util.LinkedList<Def> {
}
```

The classes have more methods: constructors, equality, visitors.

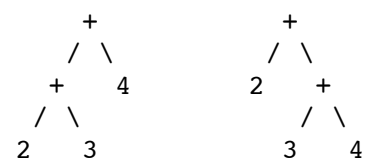
Syntax-directed translation is implemented with visitors (later lecture).

Ambiguity

What is the syntax tree for this string?

```
2 + 3 + 4
```

Two possibilities are permitted by the grammar:



Now, the arithmetic value is the same for both, so one might think it doesn't matter. But just add minus to the grammar, and consider

```
4 - 3 - 2
```

The above grammar is **ambiguous**: it gives more than one parse result for some strings.

Sometimes the ambiguity does not affect the meaning, sometimes it does.

Programming languages in general avoid ambiguity.

Parentheses, ssociativity and precedence

One way to avoid ambiguity in a language is to use parentheses:

```
Exp ::= "(" Exp "-" Exp ")"
```

Then the programmer is forced to write either of

```
(4 - (3 -2))     ((4 - 3) - 2)
```

However, it is much convenient to have conventions on parsing (and evaluation order):

- **left associativity** - group as long left as possible:

  ```
  4 - 3 - 2    ==  (4 - 3) - 2
  ```

- **precedence** - e.g. times "binds stronger" than plus:

  ```
  4 + 3 * 2    ==   4 + (3 * 2)
  ```

Parentheses always have priority over precedence and associativity:

```
(4 + 3) * 2  !=   4 + 3 * 2
```

Precedence levels in BNFC

Having precedence and associativity rules in addition to grammar can be messy.

But they can simply be encoded in a BNF grammar by using **precedence levels**: numeral subscripts to categories. Convention: `Exp = Exp0`.

```
EInt.   Exp3 ::= Integer
ETimes. Exp2 ::= Exp2 "*" Exp3
EPlus.  Exp1 ::= Exp1 "+" Exp2
```

The following rules implement **coercions** between precedence levels.

```
_. Exp3 ::= "(" Exp ")"
_. Exp2 ::= Exp3
_. Exp1 ::= Exp2
_. Exp  ::= Exp1
```

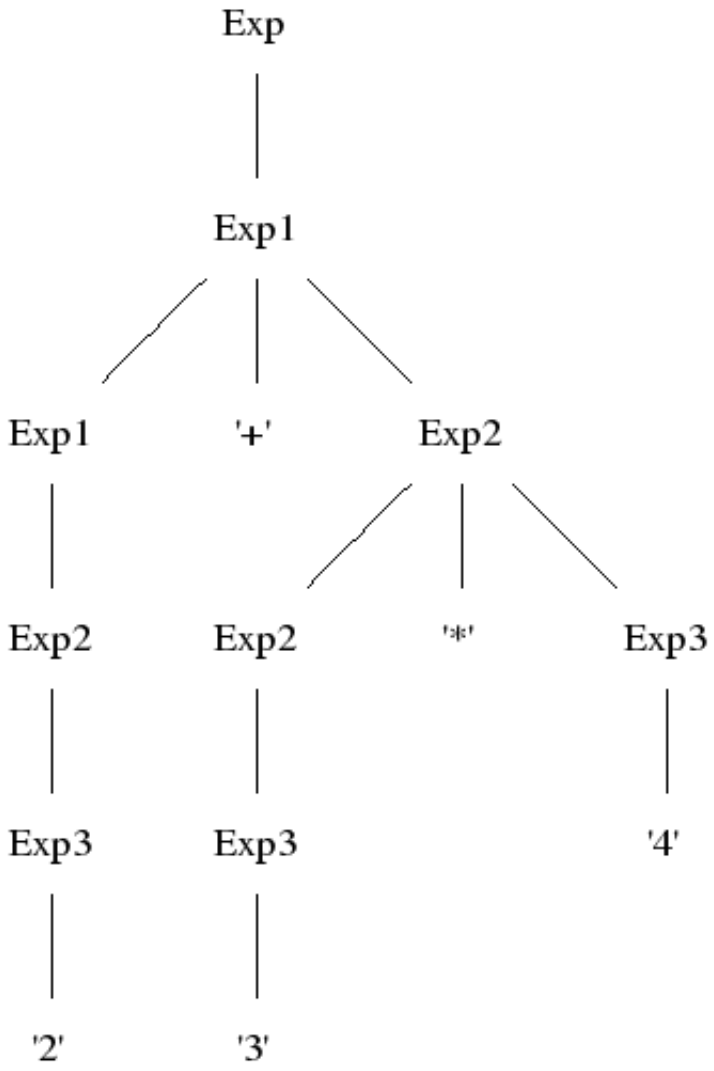
Coercions are **semantic dummies**: they add nothing to the abstract syntax tree. The symbol _ on the constructor place is used to indicate this.

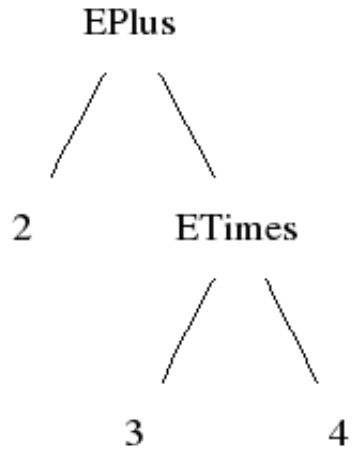
A shorthand for such coercions groups is available:

```
coercions Exp 3 ;
```

Precedence levels and trees

By definition, parse trees show coercions but abstract trees don't.





A complete grammar Imp.cf

```
Mod.   Module ::= [Def] ;

Fun.   Def    ::= Header "{" [Stm] "}" ;

terminator Def "" ;

Head.  Header ::= Type Ident "(" [Decl] ")" ;

SDecl. Stm    ::= Decl ;
SExp.  Stm    ::= Exp ;
SRet.  Stm    ::= "return" Exp ;

terminator Stm ";" ;

DTyp.  Decl   ::= Type Ident ;

separator Decl "," ;

EId.   Exp2   ::= Ident ;
ECall. Exp1   ::= Ident "(" [Exp] ")" ;
```

```
EAss.  Exp1   ::= Ident "=" Exp1 ;
EPlus. Exp    ::= Exp "+" Exp1 ;

coercions Exp 2 ;

separator Exp "," ;

TInt.  Type   ::= "int" ;
```

A quick run with BNFC

Install BNFC: see

```
http://digitalgrammars.com/bnfc/
```

Generate parser and other files from the grammar

```
bnfc -m Imp.cf
```

Compile a test program

```
make
```

Run the test program on file `koe.imp`

```
./TestImp koe.imp
```

How to approach lab 1

You can proceed by modifying `Imp.cf`

We will make a quick tour of Lab 1 PM

Have a tight modify-compile-test loop!

More practical details in next Tuesday's lecture.