Declarative Syntax Definition

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Syntax

What is Syntax?

In linguistics, **syntax** (/ˈsɪntæks/[1][2]) is the set of rules, principles, and processes that govern the structure of sentences in a given language, specifically word order and punctuation.

The term *syntax* is also used to refer to the study of such principles and processes.[3]

The goal of many syntacticians is to discover the syntactic rules common to all languages.

In mathematics, *syntax* refers to the rules governing the behavior of mathematical systems, such as formal languages used in logic. (See logical syntax.)

The word *syntax* comes from Ancient Greek: σύνταξις "coordination", which consists of σύν *syn*, "together," and τάξις *táxis*, "an ordering".

https://en.wikipedia.org/wiki/Syntax

Syntax (Programming Languages)

In computer science, the **syntax** of a computer language is the set of rules that defines the combinations of symbols that are considered to be a correctly structured document or fragment in that language.

This applies both to programming languages, where the document represents source code, and markup languages, where the document represents data.

The syntax of a language defines its surface form.[1]

Text-based computer languages are based on sequences of characters, while visual programming languages are based on the spatial layout and connections between symbols (which may be textual or graphical).

Documents that are syntactically invalid are said to have a syntax error.

https://en.wikipedia.org/wiki/Syntax_(programming_languages)

Syntax

- The set of rules, principles, and processes that govern the structure of sentences in a given language
- The set of rules that defines the combinations of symbols that are considered to be a correctly structured document or fragment in that language

How to describe such a set of rules?

The Structure of Programs

What do we call the elements of programs?

```c
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

What kind of program element is this?

```c
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Program

Compilation Unit

What kind of program element is this?

```c
#include <stdio.h>
```

Preprocessor Directive

```c
int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
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  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Function Declaration

Function Prototype

What kind of program element is this?

```c
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Comment

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Function Definition

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Variable Declaration

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Statement

For Loop

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Statement

Function Call

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Expression

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Formal Function Parameter

What kind of program element is this?

```
#include <stdio.h>

int power(int m, int n);

/* test power function */
main() {
  int i;
  for (i = 0; i < 10; ++i)
    printf("%d %d %d\n", i, power(2, i), power(-3, i));
  return 0;
}

/* power: raise base to n-th power; n >= 0 */
int power(int base, int n) {
  int i, p;
  p = 1;
  for (i = 1; i <= n; ++i)
    p = p * base;
  return p;
}
```

Type

Syntactic Categories

Preprocessor Directive

For Loop

Function Declaration

Compilation Unit

Function Prototype

Program

Statement

Function Call

Variable Declaration

Function Definition

Type

Formal Function Parameter

Expression

Programs consist of different *kinds* of elements

Hierarchy of Syntactic Categories

Program

Compilation Unit

Preprocessor Directive

Function Definition

Function Declaration
Function Prototype

Variable Declaration

Statement

Type

Expression

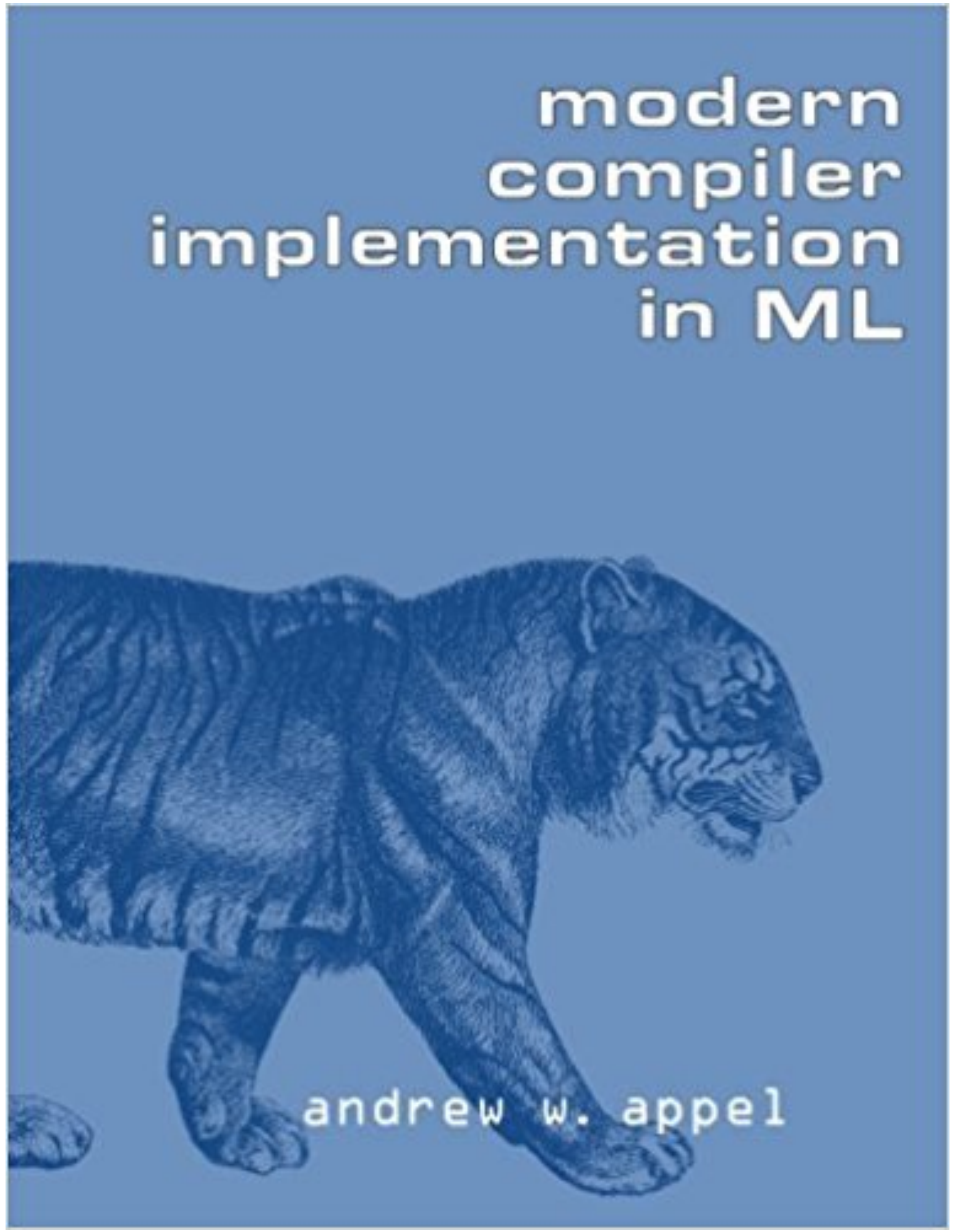
For Loop

Formal Function Parameter

Function Call

Some kinds of constructs are *contained* in others

The Tiger Language



Example language used in lectures

Documentation

https://www.lrde.epita.fr/~tiger/tiger.html

Spoofax project

https://github.com/MetaBorgCube/metaborg-tiger

```
let
  var N := 8
  type intArray = array of int
  var row := intArray[N] of 0
  var col := intArray[N] of 0
  var diag1 := intArray[N + N - 1] of 0
  var diag2 := intArray[N + N - 1] of 0
  function printboard() = (
      for i := 0 to N - 1 do (
          for j := 0 to N - 1 do
            print(if col[i] = j then
              " O"
            else
              " .");
          print("\n")
        );
      print("\n"))
  function try(c : int) = (
      if c = N then
        printboard()
      else
        for r := 0 to N - 1 do
          if row[r] = 0 & diag1[r + c] = 0 & diag2[r + 7 - c] = 0 then (
              row[r] := 1;
              diag1[r + c] := 1;
              diag2[r + 7 - c] := 1;
              col[c] := r;
              try(c + 1);
              row[r] := 0;
              diag1[r + c] := 0;
              diag2[r + 7 - c] := 0))
 in
  try(0)
end
```

A Tiger program that solves the n-queens problem

Elements of Programs

Structure

- Programs have structure

Categories

- Program elements come in multiple categories
- Elements cannot be arbitrarily interchanged

Constructs

- Some categories have multiple elements

Hierarchy

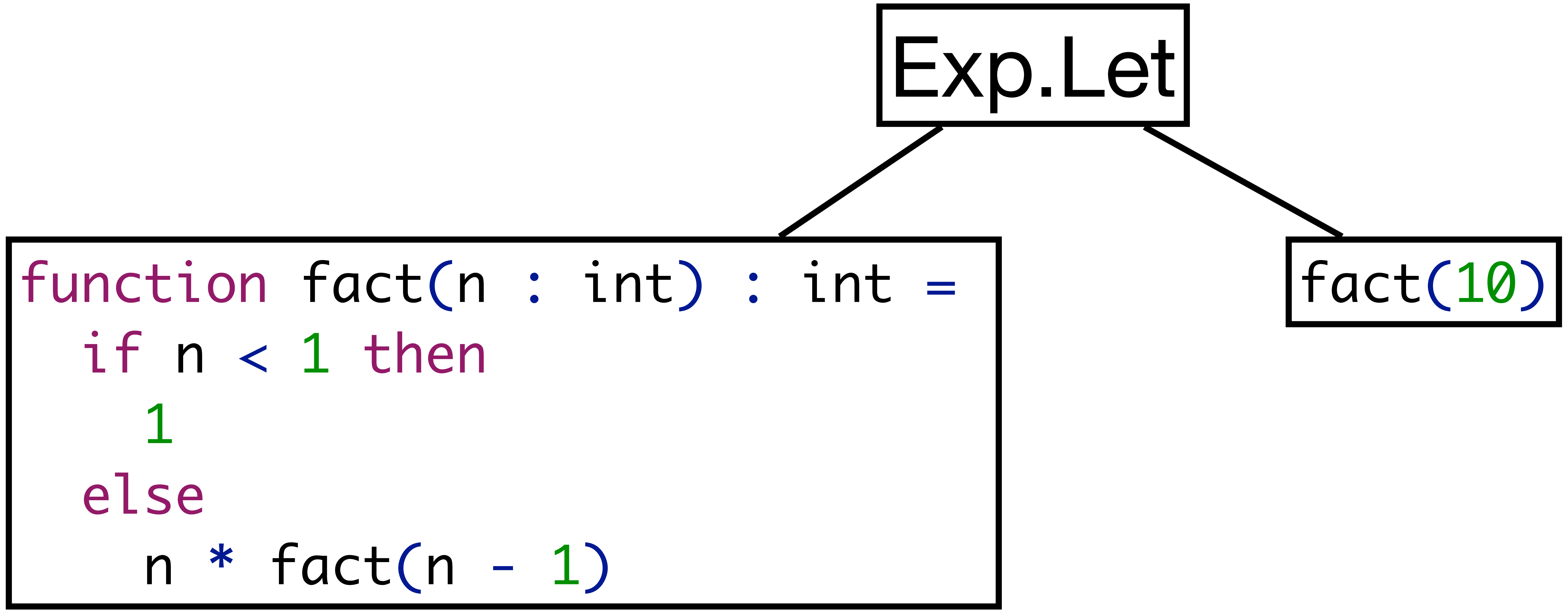
- Categories are organized in a hierarchy

Decomposing Programs

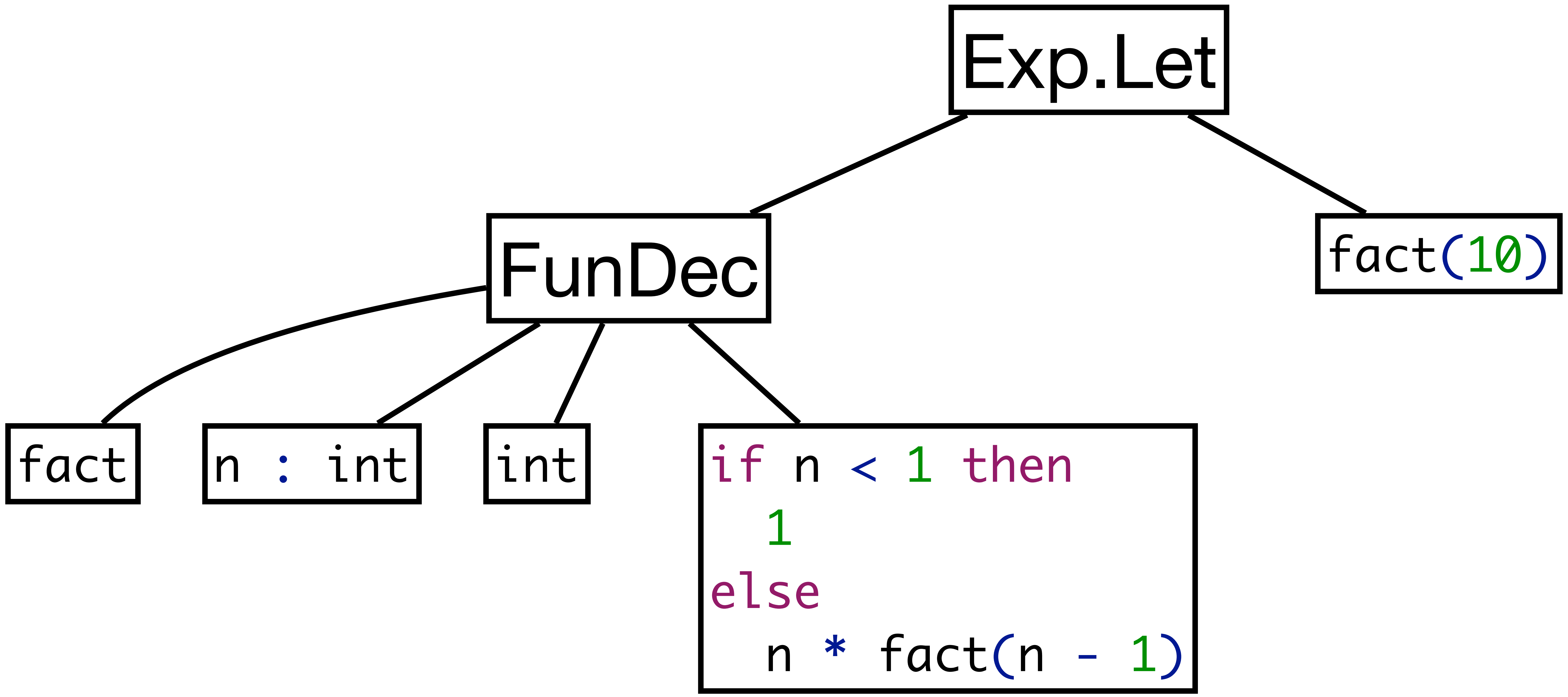
Decomposing a Program into Elements

```
let function fact(n : int) : int =
      if n < 1 then
        1
      else
        n * fact(n - 1)
 in
    fact(10)
end
```

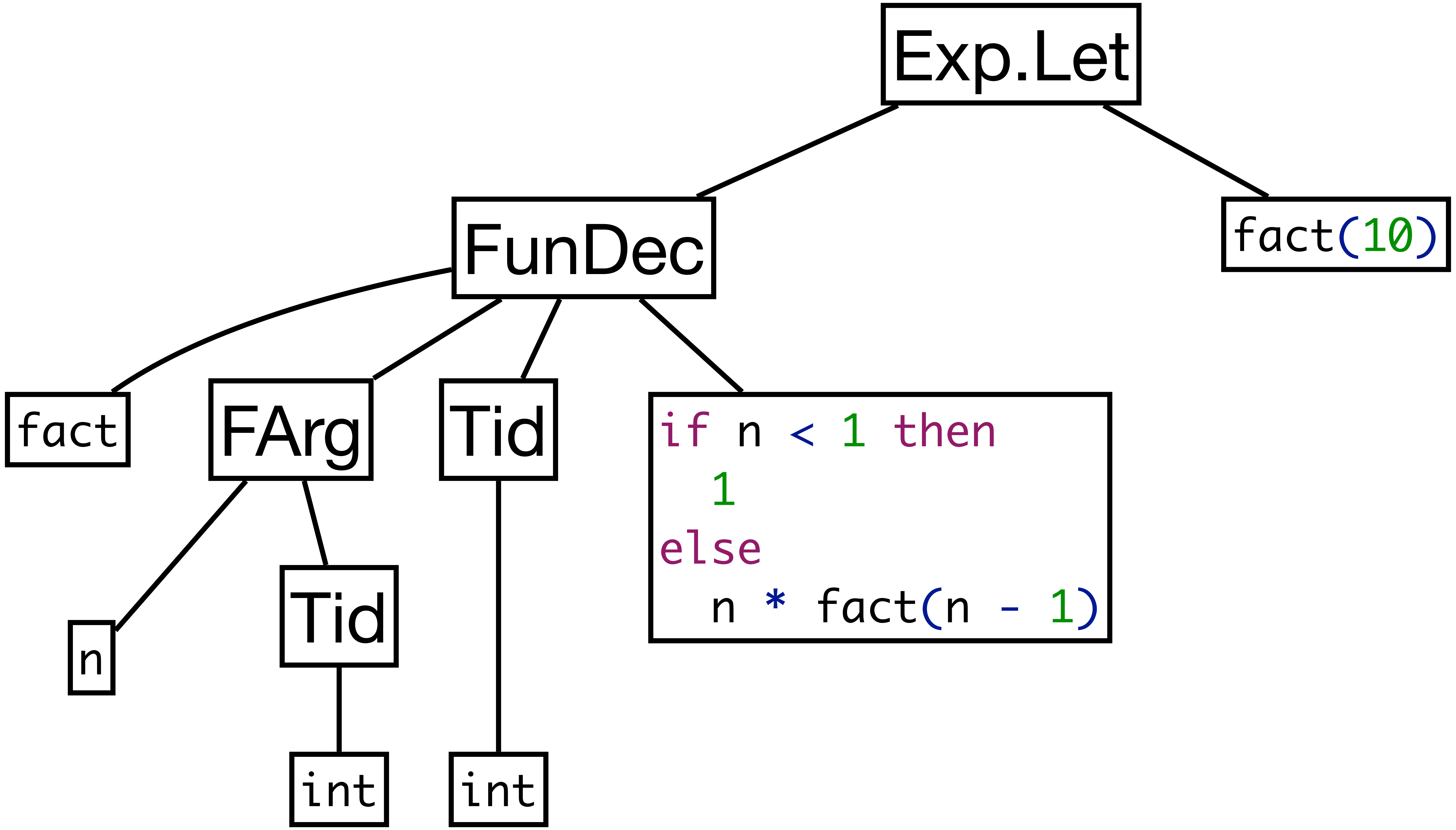
Decomposing a Program into Elements



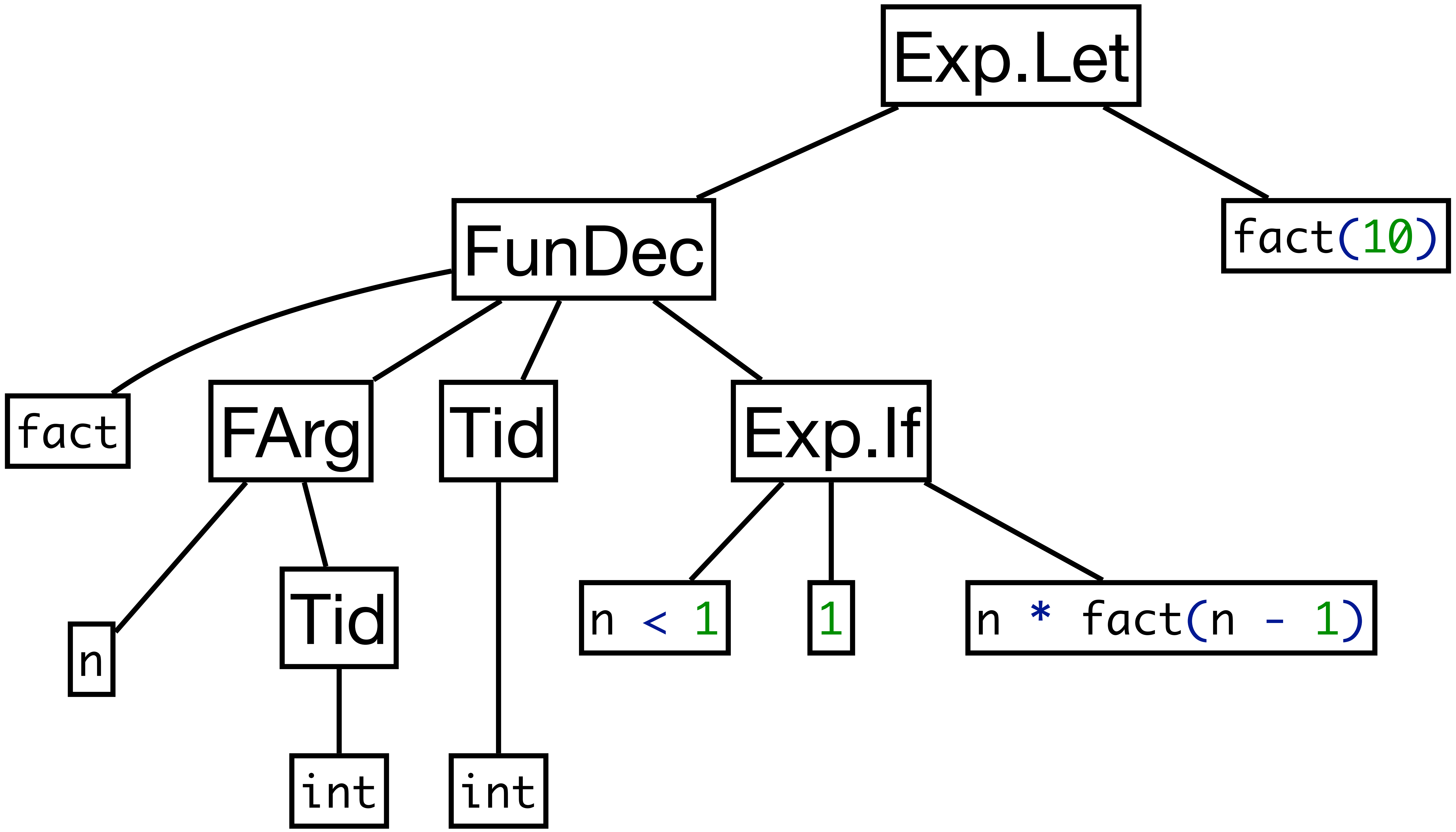
Decomposing a Program into Elements



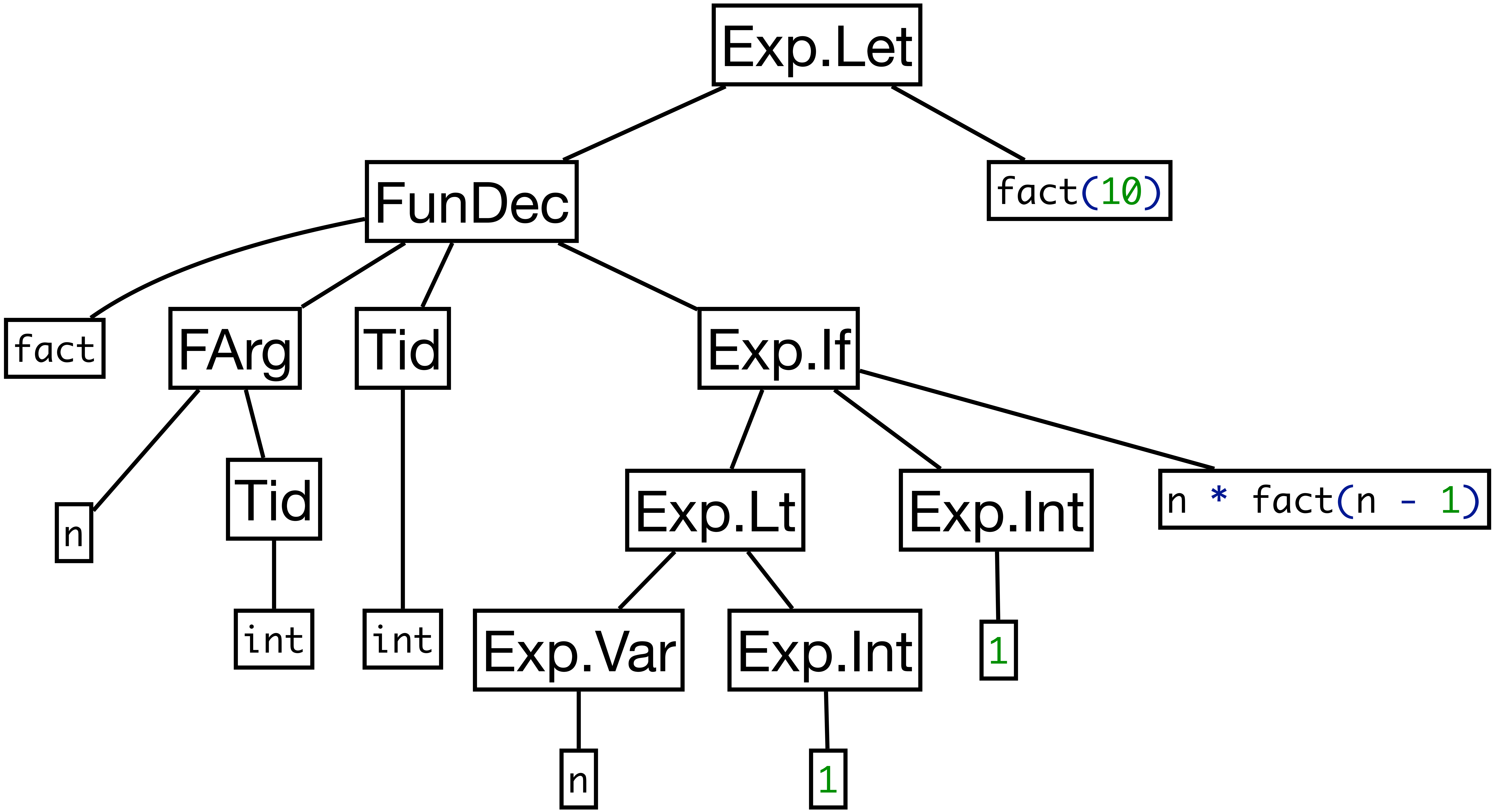
Decomposing a Program into Elements



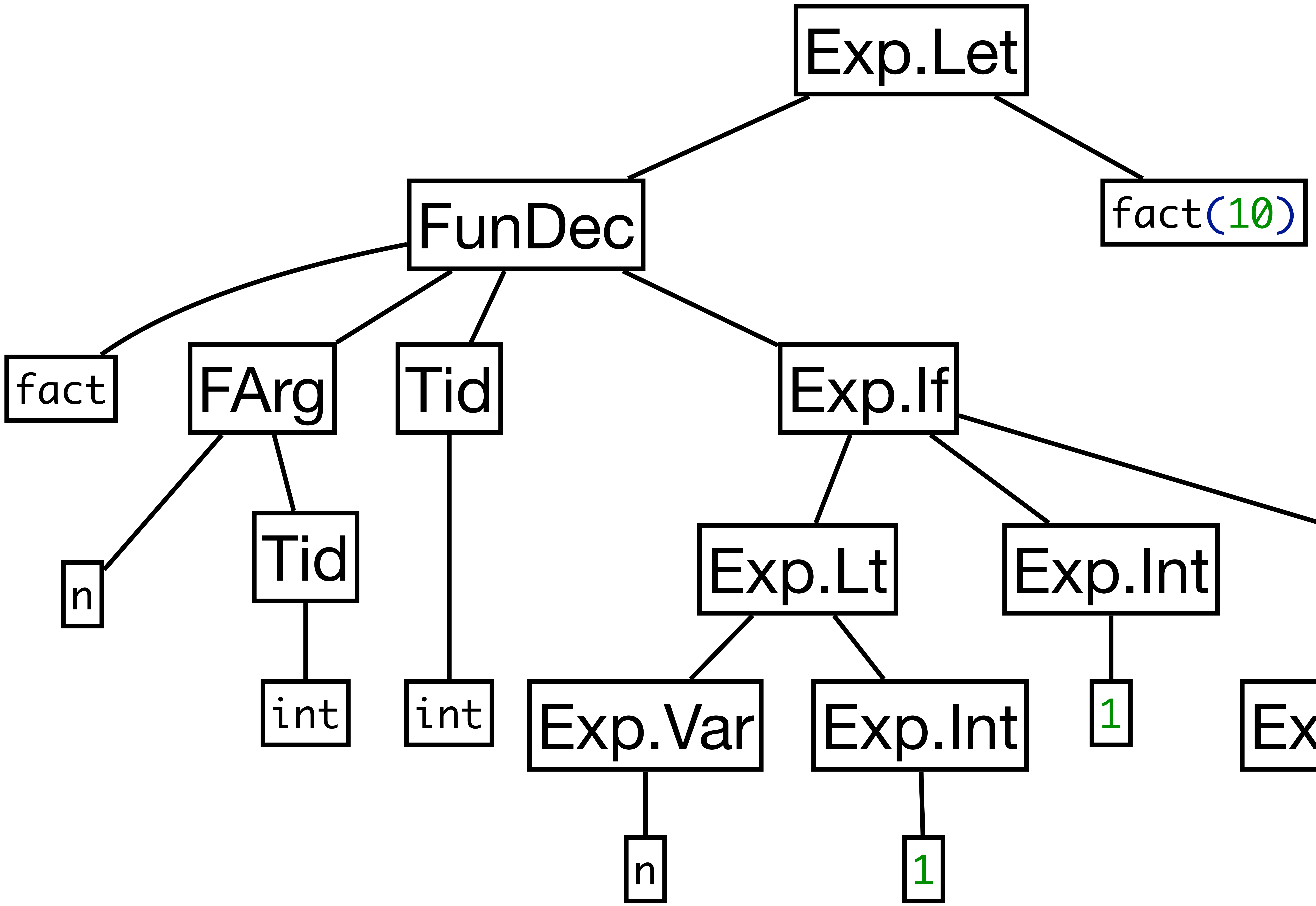
Decomposing a Program into Elements



Decomposing a Program into Elements



Decomposing a Program into Elements




```
let function fact(n : int) : int =
      if n < 1 then
        1
      else
        n * fact(n - 1)
 in
    fact(10)
end
```

Etc.

Tree Structure Represented as (First-Order) Term

```
let function fact(n : int) : int =
      if n < 1 then
        1
      else
        n * fact(n - 1)
 in
    fact(10)
end
```

```
Mod(
  Let(
    [ FunDecs(
        [ FunDec(
            "fact"
          , [FArg("n", Tid("int"))]
          , Tid("int")
          , If(
              Lt(Var("n"), Int("1"))
            , Int("1")
            , Times(
                Var("n")
              , Call("fact", [Minus(Var("n"), Int("1"))])
              )
            )
          )
        ]
      )
    ]
  , [Call("fact", [Int("10")])]
  )
)
```

Decomposing Programs

Textual representation

- Convenient to read and write (human processing)
- Concrete syntax / notation

Structural tree/term representation

- Represents the decomposition of a program into elements
- Convenient for machine processing
- Abstract syntax

Formalizing Program Decomposition

What are well-formed textual programs?

What are well-formed terms/trees?

How to decompose programs automatically?

Abstract Syntax: Formalizing Program Structure

Algebraic Signatures

```
signature
  sorts S0 S1 S2 …
  constructors
    C : S1 * S2 * … -> S0
    …
```

Sorts: syntactic categories

Constructors: language constructs

Well-Formed Terms

The family of well-formed terms T(Sig)

defined by signature Sig

is inductively defined as follows:

If C : S1 * S2 * … -> S0 is a constructor in Sig and

if t1, t2, … are terms in T(Sig)(S1), T(Sig)(S2), …,

then C(t1, t2, …) is a term in T(Sig)(S0)

Well-Formed Terms: Example

```
if n < 1 then
  1
else
  n * fact(n - 1)
```

decompose

```
If(
  Lt(Var("n"), Int("1"))
, Int("1")
, Times(
    Var("n")
    , Call("fact", [Minus(Var("n"), Int("1"))])
  )
)
```

well-formed wrt

```
signature
  sorts Exp
  constructors
    Int   : IntConst -> Exp
    Var   : ID -> Exp
    Times : Exp * Exp -> Exp
    Minus : Exp * Exp -> Exp
    Lt    : Exp * Exp -> Exp
    If    : Exp * Exp * Exp -> Exp
    Call  : ID * List(Exp) -> Exp
```

Lists of Terms

```
signature
  sorts Exp
  constructors
    …
    Call : ID * List(Exp) -> Exp
```

```
[]
```

```
[Minus(Var("n"), Int(“1”))]
```

```
[Minus(Var("n"), Int(“1”)), Lt(Var("n"), Int("1"))]
```

Well-Formed Terms with Lists

The family of well-formed terms T(Sig)

defined by signature Sig

is inductively defined as follows:

If C : S1 * S2 * … -> S0 is a constructor in Sig and
if t1, t2, … are terms in T(Sig)(S1), T(Sig)(S2), …,
then C(t1, t2, …) is a term in T(Sig)(S0)

If t1, t2, … are terms in T(Sig)(S),
Then [t1, t2, …] is a term in T(Sig)(List(S))

Abstract syntax of a language

- Defined by algebraic signature
- Sorts: syntactic categories
- Constructors: language constructs

Program structure

- Represented by (first-order) term
- Well-formed with respect to abstract syntax
- (Isomorphic to tree structure)

From Abstract Syntax to Concrete Syntax

What does Abstract Syntax Abstract from?

```
signature
  sorts Exp
  constructors
    Int   : IntConst -> Exp
    Var   : ID -> Exp
    Times : Exp * Exp -> Exp
    Minus : Exp * Exp -> Exp
    Lt    : Exp * Exp -> Exp
    If    : Exp * Exp * Exp -> Exp
    Call  : ID * List(Exp) -> Exp
```

Signature does not define ‘notation’

What is Notation?

```
signature
  sorts Exp
  constructors
    Int   : IntConst -> Exp
    Var   : ID -> Exp
    Times : Exp * Exp -> Exp
    Minus : Exp * Exp -> Exp
    Lt    : Exp * Exp -> Exp
    If    : Exp * Exp * Exp -> Exp
    Call  : ID * List(Exp) -> Exp
```

```
if n < 1 then
  1
else
  n * fact(n - 1)
```

```
n
x
e1 * e2
e1 - e2
e1 < e2
if e1 then e2 else e3
f(e1, e2, …)
```

Notation: literals, keywords, delimiters, punctuation

How can we couple notation to abstract syntax?

```
if n < 1 then
  1
else
  n * fact(n - 1)
```

```
signature
  sorts Exp
  constructors
    Int   : IntConst -> Exp
    Var   : ID -> Exp
    Times : Exp * Exp -> Exp
    Minus : Exp * Exp -> Exp
    Lt    : Exp * Exp -> Exp
    If    : Exp * Exp * Exp -> Exp
    Call  : ID * List(Exp) -> Exp
```

```
n
x
e1 * e2
e1 - e2
e1 < e2
if e1 then e2 else e3
f(e1, e2, …)
```

Notation: literals, keywords, delimiters, punctuation

Context-Free Grammars

```
grammar
  non-terminals N0 N1 N2 …
  terminals T0 T1 T2 …
  productions
    N0 = S1 S2 …
    …
```

Non-terminals (N): syntactic categories

Terminals (T): words of sentences

Symbols (S): non-terminals and terminals

Productions: rules to create sentences

Well-Formed Sentences

The family of sentences L(G) defined by context-free grammar G is inductively defined as follows:

A terminal T is a sentence in L(G)(T)

If N0 = S1 S2 … is a production in G and
if w1, w2, … are sentences in L(G)(S1), L(G)(S2), …,
then w1 w2 … is a sentence in L(G)(N0)

Well-Formed Sentences

```
if n < 1 then
  1
else
  n * fact(n - 1)
```

```
grammar
non-terminals Exp
productions
  Exp = IntConst
  Exp = Id
  Exp = Exp "*" Exp
  Exp = Exp "-" Exp
  Exp = Exp "<" Exp
  Exp = "if" Exp "then" Exp "else" Exp
  Exp = Id "(" {Exp ","}* ")"
```

What is the relation between concrete and abstract syntax?

```
if n < 1 then
  1
else
  n * fact(n - 1)
```

?

```
If(
  Lt(Var("n"), Int("1"))
, Int("1")
, Times(
    Var("n")
    , Call("fact", [Minus(Var("n"), Int("1"))])
  )
)
```

```
grammar
non-terminals Exp
productions
  Exp = IntConst
  Exp = Id
  Exp = Exp "*" Exp
  Exp = Exp "-" Exp
  Exp = Exp "<" Exp
  Exp = "if" Exp "then" Exp "else" Exp
  Exp = Id "(" {Exp ","}* ")"
```

?

```
signature
  sorts Exp
  constructors
    Int   : IntConst -> Exp
    Var   : ID -> Exp
    Times : Exp * Exp -> Exp
    Minus : Exp * Exp -> Exp
    Lt    : Exp * Exp -> Exp
    If    : Exp * Exp * Exp -> Exp
    Call  : ID * List(Exp) -> Exp
```

Context-Free Grammars with Constructor Declarations

```
sorts Exp
context-free syntax
  Exp.Int   = IntConst
  Exp.Var   = Id
  Exp.Times = Exp "*" Exp
  Exp.Minus = Exp "-" Exp
  Exp.Lt    = Exp "<" Exp
  Exp.If    = "if" Exp "then" Exp "else" Exp
  Exp.Call  = Id "(" {Exp ","}* ")"
```

```
grammar
non-terminals Exp
productions
  Exp = IntConst
  Exp = Id
  Exp = Exp "*" Exp
  Exp = Exp "-" Exp
  Exp = Exp "<" Exp
  Exp = "if" Exp "then" Exp "else" Exp
  Exp = Id "(" {Exp ","}* ")"
```

```
signature
  sorts Exp
  constructors
    Int   : IntConst -> Exp
    Var   : ID -> Exp
    Times : Exp * Exp -> Exp
    Minus : Exp * Exp -> Exp
    Lt    : Exp * Exp -> Exp
    If    : Exp * Exp * Exp -> Exp
    Call  : ID * List(Exp) -> Exp
```

Context-Free Grammars with Constructor Declarations

```
sorts Exp
context-free syntax
  Exp.Int   = IntConst
  Exp.Var   = Id
  Exp.Times = Exp "*" Exp
  Exp.Minus = Exp "-" Exp
  Exp.Lt    = Exp "<" Exp
  Exp.If    = "if" Exp "then" Exp "else" Exp
  Exp.Call  = Id "(" {Exp ","}* ")"
```

Abstract syntax: productions define constructor and sorts of arguments

Concrete syntax: productions define notation for language constructs

CFG with Constructors defines Abstract and Concrete Syntax

Abstract syntax

- Production defines constructor, argument sorts, result sort
- Abstract from notation: lexical elements of productions

Concrete syntax

- Productions define context-free grammar rules

Some details to discuss

- Ambiguities
- Sequences
- Lexical syntax
- Converting text to tree and back (parsing, unparsing)

Sequences (Lists)

Encoding Sequences (Lists)

```
printlist(merge(list1,list2))
```

```
Call("printlist"
    , [Call("merge", [Var("list1")
                     , Var("list2")])]
    )
```

```
sorts Exp
context-free syntax
  Exp.Int   = IntConst
  Exp.Var   = Id
  Exp.Times = Exp "*" Exp
  Exp.Minus = Exp "-" Exp
  Exp.Lt    = Exp "<" Exp
  Exp.If    = "if" Exp "then" Exp "else" Exp
  Exp.Call  = Id "(" ExpList ")"

  ExpList.Nil =
  ExpList     = ExpListNE

  ExpListNE.One  = Exp
  ExpListNE.Snoc = ExpListNE “," Exp
```

Sugar for Sequences and Optionals

```
printlist(merge(list1,list2))
```

```
Call("printlist"
    , [Call("merge", [Var("list1")
                     , Var("list2")])]
    )
```

```
context-free syntax

  Exp.Call  = Id "(" {Exp ","}* ")"
```

```
context-free syntax

  // automatically generated

  {Exp ","}*.Nil = // empty list
  {Exp ","}*     = {Exp ","}+

  {Exp ","}+.One  = Exp
  {Exp ","}+.Snoc = {Exp ","}+ "," Exp

  Exp*.Nil  = // empty list
  Exp*      = Exp+

  Exp+.One  = Exp
  Exp+.Snoc = Exp+ Exp

  Exp?.None =     // no expression
  Exp?.Some = Exp // one expression
```

Normalizing Lists

```
rules

  Snoc(Nil(), x) -> Cons(x, Nil())
  Snoc(Cons(x, xs), y) -> Cons(x, Snoc(xs, y))

  One(x) -> Cons(x, Nil())

  Nil() -> []
  Cons(x, xs) -> [x | xs]
```

```
context-free syntax

  // automatically generated

  {Exp ","}*.Nil = // empty list
  {Exp ","}*     = {Exp ","}+

  {Exp ","}+.One  = Exp
  {Exp ","}+.Snoc = {Exp ","}+ "," Exp

  Exp*.Nil  = // empty list
  Exp*      = Exp+

  Exp+.One  = Exp
  Exp+.Snoc = Exp+ Exp

  Exp?.None =     // no expression
  Exp?.Some = Exp // one expression
```

Using Sugar for Sequences

```
module Functions

imports Identifiers
imports Types

context-free syntax

  Dec     = FunDec+
  FunDec = "function" Id "(" {FArg ","}* ")" "=" Exp
  FunDec = "function" Id "(" {FArg ","}* ")" ":" Type "=" Exp
  FArg    = Id ":" Type
  Exp     = Id "(" {Exp ","}* ")"
```

```
let function power(x: int, n: int): int =
      if n <= 0 then 1
      else x * power(x, n - 1)
 in power(3, 10)
end
```

```
module Bindings

imports Control-Flow Identifiers Types Functions Variables

sorts Declarations
context-free syntax

  Exp          = "let" Dec* "in" {Exp ";"}* "end"
  Declarations = "declarations" Dec*
```

Lexical Syntax

Context-Free Syntax vs Lexical Syntax

```
let function power(x: int, n: int): int =
      if n <= 0 then 1
      else x * power(x, n - 1)
 in power(3, 10)
end
```

```
Mod(
  Let(
    [ FunDecs(
        [ FunDec(
            "power"
          , [FArg("x", Tid("int")), FArg("n", Tid("int"))]
          , Tid("int")
          , If(
              Leq(Var("n"), Int("0"))
            , Int("1")
            , Times(
                Var("x")
              , Call(
                  "power"
                , [Var("x"), Minus(Var("n"), Int("1"))]
                )
              )
            )
          )
        ]
      )
    ]
  , [Call("power", [Int("3"), Int("10")])]
  )
)
```

phrase structure

separated by layout

lexeme / token

not separated by layout

structure not relevant

Character Classes

```
lexical syntax // character codes

  Character  = [\65]

  Range      = [\65-\90]

  Union      = [\65-\90] \/ [\97-\122]

  Difference = [\0-\127] / [\10\13]

  Union      = [\0-\9\11-\12\14-\255]
```

Character class represents choice from a set of characters

Sugar for Character Classes

```
lexical syntax // sugar

  CharSugar  = [a]
             = [\97]

  CharClass  = [abcdefghijklmnopqrstuvwxyz]
             = [\97-\122]

  SugarRange = [a-z]
             = [\97-\122]

  Union      = [a-z] \/ [A-Z] \/ [0-9]
             = [\48-\57\65-\90\97-\122]

  RangeCombi = [a-z0-9\_]
             = [\48-\57\95\97-\122]

  Complement = ~[\n\r]
             = [\0-\255] / [\10\13]
             = [\0-\9\11-\12\14-\255]
```

Literals are Sequences of Characters

```
lexical syntax // literals

  Literal          = "then" // case sensitive sequence of characters

  CaseInsensitive = 'then' // case insensitive sequence of characters
```

```
syntax

  "then" = [t] [h] [e] [n]
  'then' = [Tt] [Hh] [Ee] [Nn]
```

```
syntax

  "then" = [\116] [\104] [\101] [\110]
  'then' = [\84\116] [\72\104] [\69\101] [\78\110]
```

Identifiers

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
```

```
Id = a
Id = B
Id = cD
Id = xyz10
Id = internal_
Id = CamelCase
Id = lower_case
Id = ...
```

Lexical Ambiguity: Longest Match

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
context-free syntax
  Exp.Var  = Id
  Exp.Call = Exp Exp {left} // curried function call
```

```
ab
```

```
Mod(
  amb(
    [Var("ab"),
     Call(Var("a"), Var("b"))]
  )
)
```

Lexical Ambiguity: Longest Match

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
context-free syntax
  Exp.Var  = Id
  Exp.Call = Exp Exp {left} // curried function call
```

```
abc
```

```
Mod(
  amb(
    [ amb(
        [ Var("abc")
        , Call(
            amb(
              [Var("ab"), Call(Var("a"), Var("b"))]
            )
          , Var("c")
          )
        ]
      )
    , Call(Var("a"), Var("bc"))
    ]
  )
)
```

Lexical Restriction => Longest Match

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
lexical restrictions
  Id -/- [a-zA-Z0-9\_] // longest match for identifiers
context-free syntax
  Exp.Var  = Id
  Exp.Call = Exp Exp {left} // curried function call
```

```
abc def ghi
```

```
Call(Call(Var("abc"), Var("def")), Var("ghi"))
```

Lexical restriction: phrase cannot be followed by character in character class

Lexical Ambiguity: Keywords overlap with Identifiers

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
lexical restrictions
  Id -/- [a-zA-Z0-9\_] // longest match for identifiers
context-free syntax
  Exp.Var     = Id
  Exp.Call    = Exp Exp {left}
  Exp.IfThen = "if" Exp "then" Exp
```

```
if def then ghi
```

```
amb(
  [ Mod(
      Call(
        Call(Call(Var("if"), Var("def")), Var("then"))
      , Var("ghi")
      )
    )
  , Mod(IfThen(Var("def"), Var("ghi")))
  ]
)
```

Lexical Ambiguity: Keywords overlap with Identifiers

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
lexical restrictions
  Id -/- [a-zA-Z0-9\_] // longest match for identifiers
context-free syntax
  Exp.Var     = Id
  Exp.Call    = Exp Exp {left}
  Exp.IfThen = "if" Exp "then" Exp
```

```
ifdef then ghi
```

⇒

```
amb(
  [ Mod(
      Call(Call(Var("ifdef"), Var("then")), Var("ghi"))
    )
  , Mod(IfThen(Var("def"), Var("ghi")))
  ]
)
```

Reject Productions => Reserved Words

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
  Id = "if" {reject}
  Id = "then" {reject}
lexical restrictions
  Id -/- [a-zA-Z0-9\_] // longest match for identifiers
  "if" "then" -/- [a-zA-Z0-9\_]
context-free syntax
  Exp.Var    = Id
  Exp.Call   = Exp Exp {left}
  Exp.IfThen = "if" Exp "then" Exp
```

```
if def then ghi
```

```
IfThen(Var("def"), Var("ghi"))
```

Reject Productions => Reserved Words

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
  Id = "if" {reject}
  Id = "then" {reject}
lexical restrictions
  Id -/- [a-zA-Z0-9\_] // longest match for identifiers
  "if" "then" -/- [a-zA-Z0-9\_]
context-free syntax
  Exp.Var    = Id
  Exp.Call   = Exp Exp {left}
  Exp.IfThen = "if" Exp "then" Exp
```

`ifdef then ghi` ⇒ `parse error`

`ifdef ghi` ⇒ `Call(Var(“ifdef"), Var("ghi"))`

Character-Level Grammars

Character-Level Grammars

Core language

- context-free grammar productions
- with constructors
- only character classes as terminals
- explicit definition of layout

Desugaring

- express lexical syntax in terms of character classes
- explicate layout between context-free syntax symbols
- separate lexical and context-free syntax non-terminals

Explication of Layout by Transformation

```
context-free syntax

  Exp.Int     = IntConst
  Exp.Uminus = "-" Exp
  Exp.Times  = Exp "*" Exp {left}
  Exp.Divide = Exp "/" Exp {left}
  Exp.Plus   = Exp "+" Exp {left}
```

Symbols in context-free syntax are implicitly separated by optional layout

```
syntax

  Exp-CF.Int     = IntConst-CF
  Exp-CF.Uminus = "-" LAYOUT?-CF Exp-CF
  Exp-CF.Times  = Exp-CF LAYOUT?-CF "*" LAYOUT?-CF Exp-CF {left}
  Exp-CF.Divide = Exp-CF LAYOUT?-CF "/" LAYOUT?-CF Exp-CF {left}
  Exp-CF.Plus   = Exp-CF LAYOUT?-CF "+" LAYOUT?-CF Exp-CF {left}
```

Separation of Lexical and Context-free Syntax

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
  Id = "if" {reject}
  Id = "then" {reject}
context-free syntax
  Exp.Var = Id
```

```
syntax

  Id-LEX = [\65-\90\97-\122] [\48-\57\65-\90\95\97-\122]*-LEX
  Id-LEX = "if" {reject}
  Id-LEX = "then" {reject}
  Id-CF  = Id-LEX

  Exp-CF.Var = Id-CF
```

Why Separation of Lexical and Context-Free Syntax?

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
  Id = "if" {reject}
  Id = "then" {reject}
context-free syntax
  Exp.Var = Id
```

⇓

```
syntax

  Id = [\65-\90\97-\122] [\48-\57\65-\90\95\97-\122]*
  Id = "if" {reject}
  Id = "then" {reject}
  Exp.Var = Id
```

Homework: what would go wrong if we not do this?

```
syntax

  "if"   = [\105] [\102]
  "then" = [\116] [\104] [\101] [\110]

  [\48-\57\65-\90\95\97-\122]+-LEX = [\48-\57\65-\90\95\97-\122]
  [\48-\57\65-\90\95\97-\122]+-LEX = [\48-\57\65-\90\95\97-\122]+-LEX [\48-\57\65-\90\95\97-\122]
  [\48-\57\65-\90\95\97-\122]*-LEX =
  [\48-\57\65-\90\95\97-\122]*-LEX = [\48-\57\65-\90\95\97-\122]+-LEX

  Id-LEX = [\65-\90\97-\122] [\48-\57\65-\90\95\97-\122]*-LEX
  Id-LEX = "if" {reject}
  Id-LEX = "then" {reject}
  Id-CF  = Id-LEX

  Exp-CF.Var    = Id-CF
  Exp-CF.Call   = Exp-CF LAYOUT?-CF Exp-CF {left}
  Exp-CF.IfThen = "if" LAYOUT?-CF Exp-CF LAYOUT?-CF "then" LAYOUT?-CF Exp-CF

  LAYOUT-CF  = LAYOUT-CF LAYOUT-CF {left}
  LAYOUT?-CF = LAYOUT-CF
  LAYOUT?-CF =

restrictions

  Id-LEX -/- [\48-\57\65-\90\95\97-\122]
  "if"   -/- [\48-\57\65-\90\95\97-\122]
  "then" -/- [\48-\57\65-\90\95\97-\122]

priorities

  Exp-CF.Call left Exp-CF.Call,
  LAYOUT-CF = LAYOUT-CF LAYOUT-CF  left LAYOUT-CF = LAYOUT-CF LAYOUT-CF
```

character classes as only terminals

separate lexical and context-free syntax

separate context-free symbols by optional layout

```
lexical syntax
  Id = [a-zA-Z] [a-zA-Z0-9\_]*
  Id = “if" {reject}
  Id = "then" {reject}
lexical restrictions
  Id -/- [a-zA-Z0-9\_]
  "if" "then" -/- [a-zA-Z0-9\_]
context-free syntax
  Exp.Var    = Id
  Exp.Call   = Exp Exp {left}
  Exp.IfThen = "if" Exp "then" Exp
```

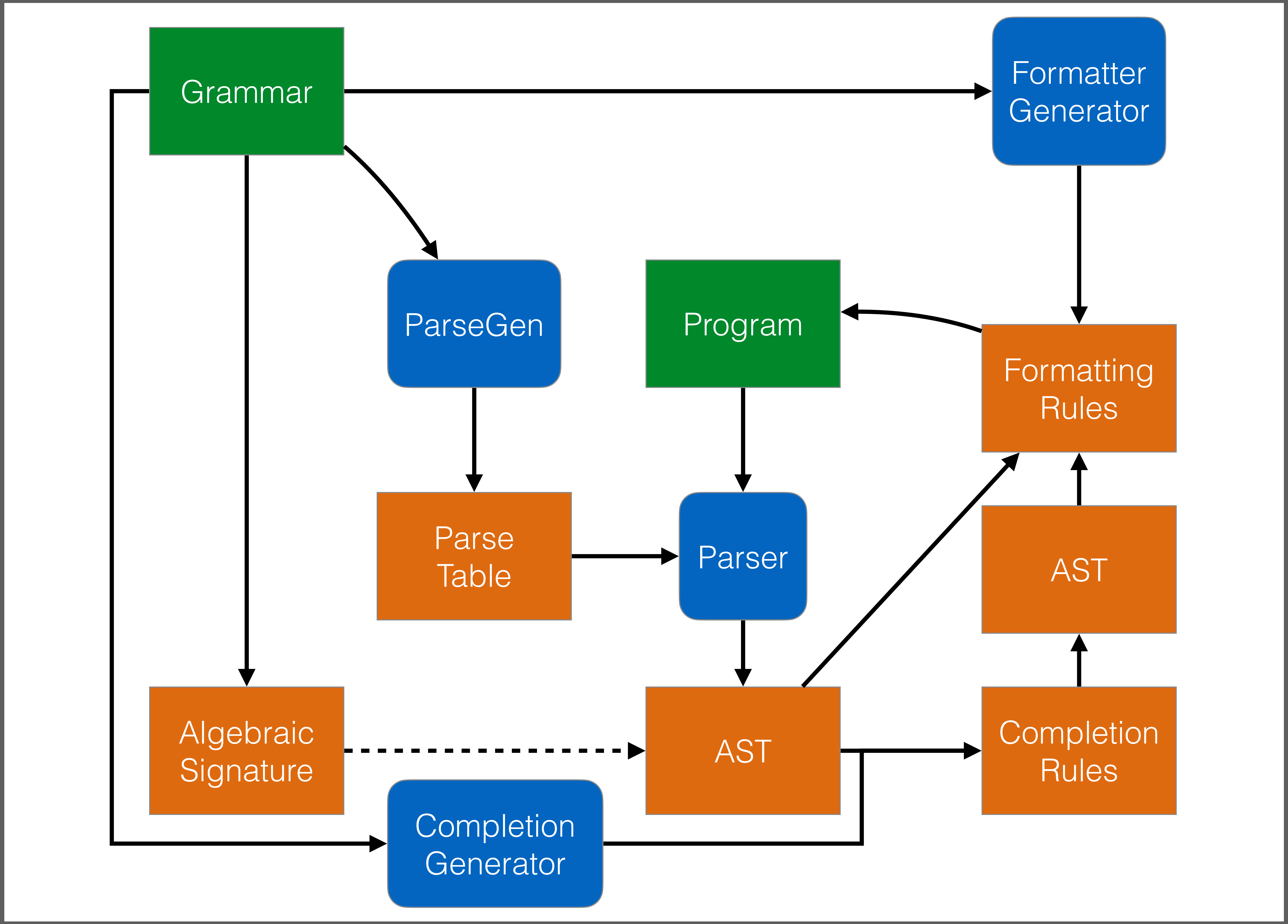
Syntax Engineering in Spoofax

Multi-Purpose Syntax Definition with SDF3

```
Statement.If = <
  if(<Exp>)
    <Statement>
  else
    <Statement>
>
```

- Parser
- Error recovery
- Pretty-printer
- Abstract syntax tree schema
- Syntactic coloring
- Syntactic completion
- Folding rules
- Outline rules

Generating Artifacts from Syntax Definitions



Syntax Engineering in Spoofax

Developing syntax definition

- Define syntax of language in multiple modules
- Syntax checking, colouring
- Checking for undefined non-terminals

Testing syntax definition

- Write example programs in editor for language under def
- Inspect abstract syntax terms
  - Spoofax > Syntax > Show Parsed AST
- Write SPT test for success and failure cases
  - Updated after build of syntax definition

workspace - Java - org.metaborg.lang.tiger/syntax/Numbers.sdf3 - Eclipse

Numbers.sdf3

```
module Numbers

lexical syntax

  IntConst = [0-9]+

lexical syntax

  RealConst.RealConstNoExp = IntConst "." IntConst
  RealConst.RealConst = IntConst "." IntConst "e" Sign IntConst
  Sign = "+"
  Sign = "-"

context-free syntax

  Exp.Int     = IntConst

  Exp.Uminus  = [- [Exp]]
  Exp.Times   = [[Exp] * [Exp]]   {left}
  Exp.Divide  = [[Exp] / [Exp]]   {left}
  Exp.Plus    = [[Exp] + [Exp]]   {left}
  Exp.Minus   = [[Exp] - [Exp]]   {left}

  Exp.Eq      = [[Exp] = [Exp]]   {non-assoc}
  Exp.Neq     = [[Exp] <> [Exp]]  {non-assoc}
  Exp.Gt      = [[Exp] > [Exp]]   {non-assoc}
  Exp.Lt      = [[Exp] < [Exp]]   {non-assoc}
  Exp.Geq     = [[Exp] >= [Exp]]  {non-assoc}
  Exp.Leq     = [[Exp] <= [Exp]]  {non-assoc}

  Exp.And     = [[Exp] & [Exp]]   {left}
  Exp.Or      = [[Exp] | [Exp]]   {left}

  //Exp = [([Exp])] {bracket, avoid}

context-free priorities

  // Precedence of operators: Unary minus has the highest
  // precedence. The operators *, / have the next highest
  // (tightest binding) precedence, followed by +, -, then
  // by =, <>, >, <, >=, <=, then by &, then by |.

  // Associativity of operators: The operators *, /, +, -
  // are all left associative. The comparison operators do
  // not associate, so a = b = c is not a legal expression,
  // a = (b = c) is legal.

  {Exp.Uminus}
  > {left :
    Exp.Times
    Exp.Divide}
```

power.tig

```
let function power(x: int, n: int): int =
      if n <= 0 then 1
      else x * power(x, n - 1)
 in power(3, 10)
end
```

power.aterm

```
Mod(
  Let(
    [ FunDecs(
        [ FunDec(
            "power"
          , [FArg("x", Tid("int")), FArg("n", Tid("int"))]
          , Tid("int")
          , If(
              Leq(Var("n"), Int("0"))
            , Int("1")
            , Times(
                Var("x")
              , Call(
                  "power"
                , [Var("x"), Minus(Var("n"), Int("1"))]
                )
              )
            )
          )
        ]
      )
    ]
  , [Call("power", [Int("3"), Int("10")])]
  )
)
```

structure.spt

```
module structure

language Tiger

test if [[
  if x then 3 else 4
]] parse to Mod(If(Var("x"),Int("3"),Int("4")))

test add times [[
  21 + 14 + 7
]] parse to Mod(Plus(Int("21"),Times(Int("14"),Int("7"))))

test times add [[
  3 * 7 + 21
]] parse to Mod(Plus(Times(Int("3"),Int("7")),Int("21")))
```

Writable | Insert | 13 : 3

Declarative Syntax Definition: Summary

Declarative Language Definition

Language definition

- Define syntax and semantics of (domain-specific) programming languages

High-level and Understandable

- Can be used as reference documentation

Executable

- Can be used to generate tools

Declarative

- No need to understand algorithms

Multi-purpose

- Derive many/all tools from single definition

Correct by Construction

- Implementations sound wrt declarative semantics

Separation of Concerns

Representation

- Standardized representation for <aspect> of programs
- Independent of specific object language

Specification Formalism

- Language-specific declarative rules
- Abstract from implementation concerns

Language-Independent Interpretation

- Formalism interpreted by language-independent algorithm
- Multiple interpretations for different purposes
- Reuse between implementations of different languages

Declarative Syntax Definition

Representation

- Syntax trees

Specification Formalism: SDF3

- Productions + Constructors + Templates + Disambiguation

Declarative Semantics

- Well-formedness of syntax trees wrt syntax definition

Language-Independent Tools

- Parser
- Formatting based on layout hints in grammar
- Syntactic completion

Declarative Syntax Definition

Syntax definition

- Define structure (decomposition) of programs
- Define concrete syntax: notation
- Define abstract syntax: constructors

Using syntax definitions (next)

- Parsing: converting text to abstract syntax term
- Pretty-printing: convert abstract syntax term to text
- Editor services: syntax highlighting, syntax checking, completion

Reading Material

This paper gives an overview of the Syntax Definition Formalism SDF3, the language for syntax definition in Spoofax and in this course.

It provides a summary of research on syntax definition that we did in the last 20 years and provides a good introduction to the features of SDF3 that we will study in the next couple of weeks.

https://doi.org/10.1007/978-3-030-58768-0_1

Multi-Purpose Syntax Definition with SDF3

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Abstract. SDF3 is a syntax definition formalism that extends plain context-free grammars with features such as constructor declarations, declarative disambiguation rules, character-level grammars, permissive syntax, layout constraints, formatting templates, placeholder syntax, and modular composition. These features support the multi-purpose interpretation of syntax definitions, including derivation of type schemas for abstract syntax tree representations, scannerless generalized parsing of the full class of context-free grammars, error recovery, layout-sensitive parsing, parenthesization and formatting, and syntactic completion. This paper gives a high level overview of SDF3 by means of examples and provides a guide to the literature for further details.

Keywords: Syntax definition · programming language · parsing.

1 Introduction

A syntax definition formalism is a formal language to describe the syntax of formal languages. At the core of a syntax definition formalism is a *grammar formalism* in the tradition of Chomsky's context-free grammars [14] and the Backus-Naur Form [4]. But syntax definition is concerned with more than just phrase structure, and encompasses all aspects of the syntax of languages.

In this paper, we give an overview of the syntax definition formalism SDF3 and its tool ecosystem that supports the multi-purpose interpretation of syntax definitions. The paper does not present any new technical contributions, but it is the first paper to give a (high-level) overview of all aspects of SDF3 and serves as a guide to the literature. SDF3 is the third generation in the SDF family of syntax definition formalisms, which were developed in the context of the ASF+SDF [5], Stratego/XT [10], and Spoofax [38] language workbenches.

The first SDF [23] supported modular composition of syntax definition, a direct correspondence between concrete and abstract syntax, and parsing with the full class of context-free grammars enabled by the Generalized-LR (GLR) parsing algorithm [56,44]. Its programming environment, as part of the ASF+SDF MetaEnvironment [40], focused on live development of syntax definitions through

To appear in: F. S. de Boer and A. Cerone (Eds.). *Software Engineering and Formal Methods (SEFM 2020)*, LNCS, Springer, 2020.

The perspective of this lecture on declarative syntax definition is explained more elaborately in this Onward! 2010 essay. It uses an on older version of SDF than used in these slides. Production rules have the form

$$X_1 \ldots X_n \texttt{ -> } N \ \{\texttt{cons("C")}\}$$

instead of

$$N.C = X_1 \ldots X_n$$

Assignment

Read this paper in preparation for Lecture 2

https://doi.org/10.1145/1932682.1869535

Pure and Declarative Syntax Definition: Paradise Lost and Regained

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Abstract

Syntax definitions are pervasive in modern software systems, and serve as the basis for language processing tools like parsers and compilers. Mainstream parser generators pose restrictions on syntax definitions that follow from their implementation algorithm. They hamper evolution, maintainability, and compositionality of syntax definitions. The pureness and declarativity of syntax definitions is lost. We analyze how these problems arise for different aspects of syntax definitions, discuss their consequences for language engineers, and show how the pure and declarative nature of syntax definitions can be regained.

Categories and Subject Descriptors D.3.1 [*Programming Languages*]: Formal Definitions and Theory — Syntax; D.3.4 [*Programming Languages*]: Processors — Parsing; D.2.3 [*Software Engineering*]: Coding Tools and Techniques

General Terms Design, Languages

Prologue

In the beginning were the *words*, and the words were *trees*, and the trees were words. All words were made through *grammars*, and without grammars was not any word made that was made. Those were the days of the garden of Eden. And there where language engineers strolling through the garden. They made languages which were sets of words by making grammars full of beauty. And with these grammars, they turned words into trees and trees into words. And the trees were natural, and pure, and beautiful, as were the grammars.

Among them were software engineers who made software as the language engineers made languages. And they dwelt with them and they were one people. The language engineers were software engineers and the software engineers were language engineers. And the language engineers made *language software*. They made *recognizers* to know words, and *generators* to make words, and *parsers* to turn words into trees, and *formatters* to turn trees into words.

But the software they made was not as natural, and pure, and beautiful as the grammars they made. So they made software to make language software and began to make language software by making *syntax definitions*. And the syntax definitions were grammars and grammars were syntax definitions. With their software, they turned syntax definitions into language software. And the syntax definitions were language software and language software were syntax definitions. And the syntax definitions were natural, and pure, and beautiful, as were the grammars.

The Fall Now the serpent was more crafty than any other beast of the field. He said to the language engineers,

> *Did you actually decide not to build any parsers?*

And the language engineers said to the serpent,

> *We build parsers, but we decided not to build others than general parsers, nor shall we try it, lest we loose our syntax definitions to be natural, and pure, and beautiful.*

But the serpent said to the language engineers,

> *You will not surely loose your syntax definitions to be natural, and pure, and beautiful. For you know that when you build particular parsers your benchmarks will be improved, and your parsers will be the best, running fast and efficient.*

So when the language engineers saw that restricted parsers were good for efficiency, and that they were a delight to the benchmarks, they made software to make efficient parsers and began to make efficient parsers by making *parser definitions*. Those days, the language engineers went out from the garden of Eden. In pain they made parser definitions all the days of their life. But the parser definitions were not grammars and grammars were not parser definitions. And by the sweat of their faces they turned parser definitions into effi-

Onward! 2010, October 17–21, 2010, Reno/Tahoe, Nevada, USA.

The SPoofax Testing (SPT) language used in the section on testing syntax definitions was introduced in this OOPSLA 2011 paper.

https://doi.org/10.1145/2076021.2048080

Integrated Language Definition Testing

Enabling Test-Driven Language Development

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Abstract

The reliability of compilers, interpreters, and development environments for programming languages is essential for effective software development and maintenance. They are often tested only as an afterthought. Languages with a smaller scope, such as domain-specific languages, often remain untested. General-purpose testing techniques and test case generation methods fall short in providing a low-threshold solution for test-driven language development. In this paper we introduce the notion of a *language-parametric testing language (LPTL)* that provides a reusable, generic basis for declaratively specifying language definition tests. We integrate the syntax, semantics, and editor services of a language under test into the LPTL for writing test inputs. This paper describes the design of an LPTL and the tool support provided for it, shows use cases using examples, and describes our implementation in the form of the Spoofax testing language.

Categories and Subject Descriptors D.2.5 [*Software Engineering*]: Testing and Debugging—Testing Tools; D.2.3 [*Software Engineering*]: Coding Tools and Techniques; D.2.6 [*Software Engineering*]: Interactive Environments

General Terms Languages, Reliability

Keywords Testing, Test-Driven Development, Language Engineering, Grammarware, Language Workbench, Domain-Specific Language, Language Embedding, Compilers, Parsers

OOPSLA'11, October 22–27, 2011, Portland, Oregon, USA.

1. Introduction

Software languages provide linguistic abstractions for a domain of computation. Tool support provided by compilers, interpreters, and integrated development environments (IDEs), allows developers to reason at a certain level of abstraction, reducing the accidental complexity involved in software development (e.g., machine-specific calling conventions and explicit memory management). *Domain-specific* languages (DSLs) further increase expressivity by restricting the scope to a particular application domain. They increase developer productivity by providing domain-specific notation, analysis, verification, and optimization.

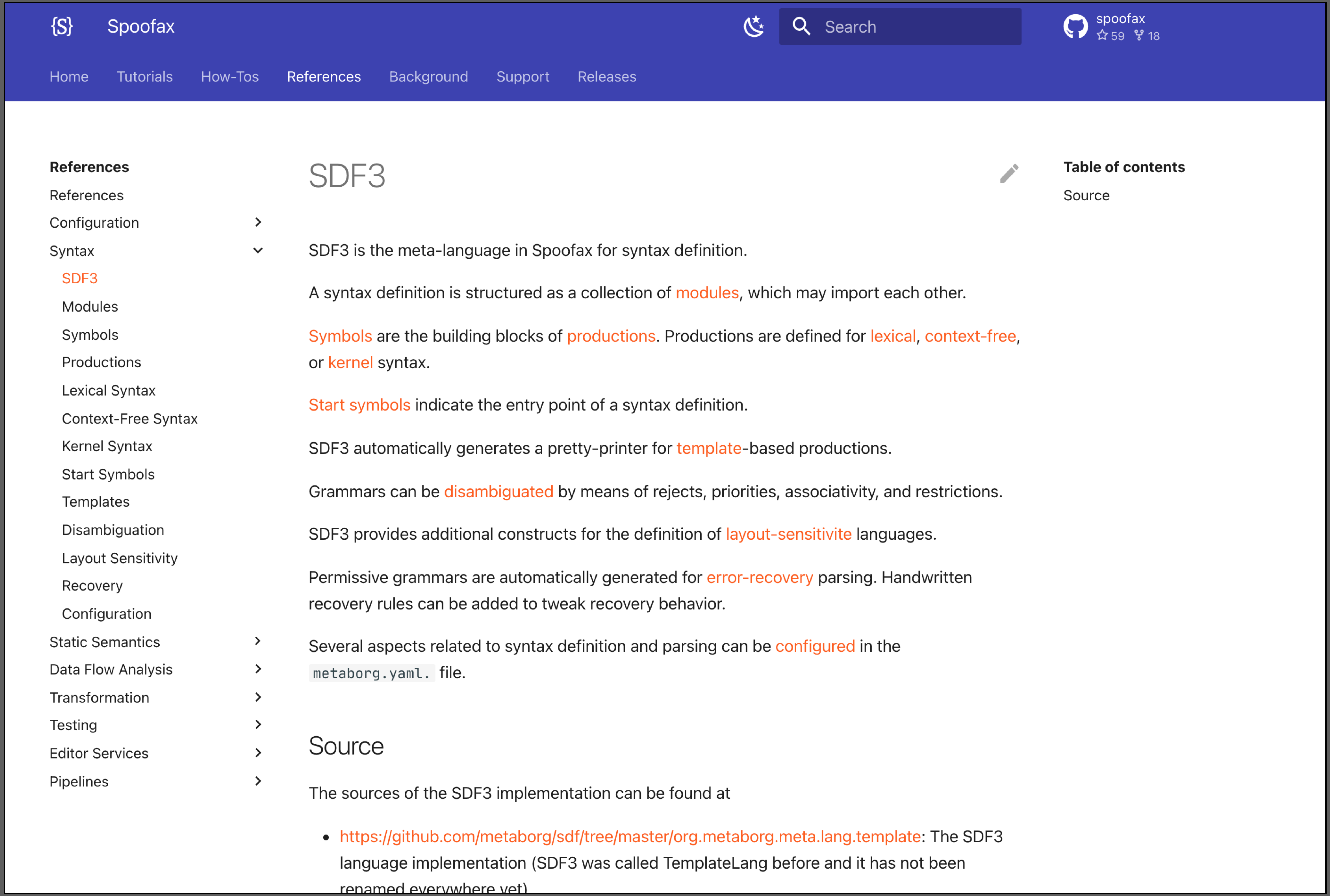
With their key role in software development, the correct implementation of languages is fundamental to the reliability of software developed with a language. Errors in compilers, interpreters, and IDEs for a language can lead to incorrect execution of correct programs, error messages about correct programs, or a lack of error messages for incorrect programs. Erroneous or incomplete language implementations can also hinder understanding and maintenance of software.

Testing is one of the most important tools for software quality control and inspires confidence in software [1]. Tests can be used as a basis for an agile, iterative development process by applying test-driven development (TDD) [1], they unambiguously communicate requirements, and they avoid regressions that may occur when new features are introduced or as an application is refactored [2, 31].

Scripts for automated testing and general-purpose testing tools such as the xUnit family of frameworks [19] have been successfully applied to implementations of general-purpose languages [16, 38] and DSLs [18, 33]. With the successes and challenges of creating such test suites by hand, there has been considerable research into *automatic generation* of compiler test suites [3, 27]. These techniques provide an effective solution for thorough black-box testing of complete compilers, by using annotated grammars to generate input programs.

Despite extensive practical and research experience in testing and test generation for languages, rather less attention has been paid to supporting language engineers in writing tests, and to applying TDD with tools specific to the do-

The SDF3 syntax definition formalism is documented at the spoofax.dev website.



{S} Spoofax

Search

spoofax ☆ 59 18

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SDF3

SDF3 is the meta-language in Spoofax for syntax definition.

A syntax definition is structured as a collection of modules, which may import each other.

Symbols are the building blocks of productions. Productions are defined for lexical, context-free, or kernel syntax.

Start symbols indicate the entry point of a syntax definition.

SDF3 automatically generates a pretty-printer for template-based productions.

Grammars can be disambiguated by means of rejects, priorities, associativity, and restrictions.

SDF3 provides additional constructs for the definition of layout-sensitivite languages.

Permissive grammars are automatically generated for error-recovery parsing. Handwritten recovery rules can be added to tweak recovery behavior.

Several aspects related to syntax definition and parsing can be configured in the `metaborg.yaml.` file.

Source

The sources of the SDF3 implementation can be found at

- https://github.com/metaborg/sdf/tree/master/org.metaborg.meta.lang.template: The SDF3 language implementation (SDF3 was called TemplateLang before and it has not been renamed everywhere yet)

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Source

https://www.spoofax.dev/references/syntax/

Next: Disambiguation