COMP3048: Lecture 3

Defining Programming Languages

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This Lecture

- Programming language definition basics.
- Backus-Naur Form (BNF) and Extended BNF (EBNF)
- Concrete Syntax
  - Lexical syntax for MiniTriangle
  - Context-free syntax for MiniTriangle
- Abstract Syntax
  - Abstract syntax for MiniTriangle
- Representing Abstract Syntax Trees (ASTs)

Syntax and Semantics (1)

The notions of ***Syntax*** and ***Semantics*** are central to any discourse on languages. Focusing on ***programming languages***:

- ***Syntax***: the ***form*** of programs
  - ***Concrete Syntax*** (or ***Surface Syntax***): What programs "look like".
    - Usually ***strings*** of characters or symbols.
    - Some languages have graphical syntax.
  - ***Abstract Syntax***: ***trees*** representing the essential structure of syntactically valid programs.

Syntax and Semantics (2)

- ***Semantics***: the ***meaning*** of programs
  - ***Static Semantics***: the static, at ***compile-time***, meaning of programs and program fragments.
    Typically aspects like scope, types.
  - ***Dynamic Semantics***: what programs and program fragments mean (or do) when executed, at ***run-time***.

Defining Programming Languages (1)

- In order to develop a compiler (or other language processor):
  - the ***Source Language*** must be defined
    - syntax
    - semantics
  - the ***Target Language*** must be defined
    - syntax
    - semantics
- Language definitions (aka ***specifications***) can be ***formal*** or ***informal***. Usually they are somewhere in between.

Defining Programming Languages (2)

Why is it important that the source and target languages are precisely defined?

- The source language syntax must be known to design the scanner and parser properly.
- The target language syntax must be known to generate syntactically correct target code.
- The semantics of both the source and target language must be known to ensure that the translation ***preserves the meaning*** of source programs; i.e. ***compiler correctness***.

Object Language and Meta Language

In any language definition, informal or formal, a careful distinction must be made between

- the ***Object Language***: the language being defined
- the ***Meta Language***: the language of the definition itself.

Moreover, the semantics of the meta language must be well understood!

Informal Specifications

- In an informal specification, the meta language is a natural language such as English.
- Most programming languages are defined more or less informally.
- “Informal” does not mean “lack of rigour”: it is possible to be precise also in a natural language.
- An example of a well-written, predominantly informal language specification is that of Java:

  `https://docs.oracle.com/javase/specs/`

Formal Specifications

A ***Formal Specification*** is mathematically precise. Usually, a ***Formal Metalanguage*** is used; e.g.:

- ***EBNF*** for specifying context-free syntax. (Int'l standard: ISO/IEC 14977:1996(E))
- ***inference rules and logic*** for specifying static and/or dynamic semantics
- ***denotational semantics*** for specifying dynamic semantics.

Context-Free Grammars

A ***Context-Free Grammar*** (CFG) formally describes a ***Context-Free Languages*** (CFL):

- The CFLs capture common programming language ideas such as
  - nested structure
  - balanced parentheses
  - matching keywords like `begin` and `end`.
- Most “reasonable” CFLs can be recognised by a simple machine: a ***deterministic pushdown automaton***.

CFG Notation (1)

We will give CFGs by stating the productions in one of two styles:

- ***Mathematical style***:
  - Used for: small, abstract examples; at ***meta level*** when talking ***about*** grammars.
  - Simple naming conventions used to distinguish terminals and non-terminals:
    - nonterminals: uppercase letters, like A, B, S
    - terminals: lowercase letters or digits, like a, b, 3
  - Start symbol usually called S.

CFG Notation (2)

- ***Programming Language Specification style:***
  - Used for larger, more realistic examples.
  - Typographical conventions used to distinguish terminals and non-terminals:
    - nonterminals are written like this
    - terminals are written like **`this`**
    - terminals with ***variable spelling*** and special symbols are written like $\underline{\mathit{this}}$
  - The start symbol is often implied by the context.

CFG Notation (3)

For example:

$$AssignStmt \rightarrow \underline{Identifier} \; \mathbf{:=} \; Expr$$

Here,

- $AssignStmt$ and $Expr$ are nonterminals
- **:=** is a terminal
- $\underline{Identifier}$ is also a terminal, but its possible spellings are defined elsewhere (usually by a ***lexical grammar***).

BNF and Extended BNF

The CFGs we have seen so far have (essentially) been expressed in ***Backus-Naur Form*** (BNF).

Extended BNF (EBNF) is a more ***convenient*** way of describing CFGs than is BNF.

- Additional EBNF constructs:
  - parentheses for grouping
  - $|$ for alternatives ***within*** parentheses
  - $*$ for iteration (W&B's notation).
- EBNF is ***no more powerful*** than BNF: any EBNF grammar can be transformed into BNF.

EBNF: Example

EBNF can transform to BNF, EBNF just a simple way of expression

The following EBNF grammar

$$Block \quad \rightarrow \quad \texttt{begin} \quad (Decl \mid Stmt)^* \quad \texttt{end}$$

(where $Decl$ and $Stmt$ are defined elsewhere) is equivalent to the following BNF grammar:

$$\begin{array}{lcl} Block & \rightarrow & \texttt{begin}\ BlockRec\ \texttt{end} \\ BlockRec & \rightarrow & \epsilon \quad \mid \quad BlockRec\ BlockAlts \\ BlockAlts & \rightarrow & Decl \quad \mid \quad Stmt \end{array}$$

Thus we see that EBNF can be quite a bit more concise and readable than plain BNF.

EBNF: ISO Notation

Watt & Brown use their own EBNF variant.

The more common variant is the ISO (International Organization for Standardization) version (ISO/IEC 14977:1996):

ISO	W&B
$\{\ A\ \}$	A^*
$[\ A\ ]$	$(A \mid \epsilon)$

MiniTriangle

The source language in the coursework is called ***MiniTriangle*** (derived from Watt & Brown).

Example:

```
let
    var y: Integer := 0
in
    begin
        y := y + 1;
        putint(y)
    end
```

Concrete Syntax

The ***Concrete Syntax***, or surface syntax, of a language is usually defined at two levels:

- The ***Lexical syntax***: the syntax of
  - ***language symbols*** or ***tokens***
  - ***white space***
  - ***comments***
- The ***Context-Free syntax***.

MiniTriangle Lexical Syntax (1)

$$
\begin{array}{lcl}
\mathit{Program} & \rightarrow & (\mathit{Token} \mid \mathit{Separator})^* \\
\mathit{Token} & \rightarrow & \mathit{Keyword} \mid \mathit{Identifier} \mid \mathit{IntegerLiteral} \mid \mathit{Operator} \\
 & & \mid \texttt{,} \mid \texttt{;} \mid \texttt{:} \mid \texttt{:=} \mid \texttt{=} \mid \texttt{(} \mid \texttt{)} \mid \underline{\mathit{eot}} \\
\mathit{Keyword} & \rightarrow & \textbf{\texttt{begin}} \mid \textbf{\texttt{const}} \mid \textbf{\texttt{do}} \mid \textbf{\texttt{else}} \mid \textbf{\texttt{end}} \mid \textbf{\texttt{if}} \mid \textbf{\texttt{in}} \\
 & & \mid \textbf{\texttt{let}} \mid \textbf{\texttt{then}} \mid \textbf{\texttt{var}} \mid \textbf{\texttt{while}} \\
\mathit{Identifier} & \rightarrow & \mathit{Letter} \mid \mathit{Identifier}\ \mathit{Letter} \mid \mathit{Identifier}\ \mathit{Digit} \\
 & & \text{except } \mathit{Keyword} \\
\mathit{IntegerLiteral} & \rightarrow & \mathit{Digit} \mid \mathit{IntegerLiteral}\ \mathit{Digit} \\
\mathit{Operator} & \rightarrow & \texttt{+} \mid \texttt{-} \mid \texttt{*} \mid \texttt{/} \mid \texttt{<} \mid \texttt{<=} \mid \texttt{==} \mid \texttt{!=} \mid \texttt{>=} \mid \texttt{>} \mid \texttt{\&\&} \mid \texttt{||} \mid \texttt{!} \\
\mathit{Separator} & \rightarrow & \mathit{Comment} \mid \underline{\mathit{space}} \mid \underline{\mathit{eol}} \\
\mathit{Comment} & \rightarrow & \texttt{//}\ (\text{any character except } \underline{\mathit{eol}})^*\ \underline{\mathit{eol}}
\end{array}
$$

MiniTriangle Lexical Syntax (2)

Notes:

- Essentially a (left-)linear grammar; i.e, the lexical syntax specifies a ***regular*** language.
- Not completely formal (e.g. the use of “except” for excluding keywords from identifiers).
- Note! Each individual character of a terminal is actually a terminal symbol! I.e., really:

  $$\text{Keyword} \rightarrow \mathtt{b\ e\ g\ i\ n} \mid \mathtt{c\ o\ n\ s\ t} \mid \ldots$$

- Special characters are written like $\underline{\mathit{this}}$. Note! They are single terminal symbols!

MiniTriangle: Tokens

Some valid MiniTriangle tokens:

- `const3` (Identifier)
- `const` (Keyword)
- `42` (Integer-Literal)
- `+` (Operator)

Q: Is `const3` really a single token?
The grammar is ***ambiguous***!

A: An implicit “***maximal munch rule***” used to disambiguate!

MiniTriangle Context-Free Syntax (1)

(Small version: other (extended) versions later.)

$$
\begin{array}{lcl}
\mathit{Program} & \rightarrow & \mathit{Command} \\
\mathit{Commands} & \rightarrow & \mathit{Command} \\
& | & \mathit{Command}\ \texttt{;}\ \mathit{Commands} \\
\mathit{Command} & \rightarrow & \mathit{VarExpression}\ \texttt{:=}\ \mathit{Expression} \\
& | & \mathit{VarExpression}\ \texttt{(}\ \mathit{Expressions}\ \texttt{)} \\
& | & \texttt{if}\ \mathit{Expression}\ \texttt{then}\ \mathit{Command}\ \texttt{else}\ \mathit{Command} \\
& | & \texttt{while}\ \mathit{Expression}\ \texttt{do}\ \mathit{Command} \\
& | & \texttt{let}\ \mathit{Declarations}\ \texttt{in}\ \mathit{Command} \\
& | & \texttt{begin}\ \mathit{Commands}\ \texttt{end}
\end{array}
$$

MiniTriangle Context-Free Syntax (2)

$$
\begin{array}{lcl}
\mathit{Expressions} & \rightarrow & \mathit{Expression} \\
 & | & \mathit{Expression}\ \mathbf{,}\ \mathit{Expressions} \\
\mathit{Expression} & \rightarrow & \mathit{PrimaryExpression} \\
 & | & \mathit{Expression}\ \underline{\mathit{Operator}}\ \mathit{PrimaryExpression} \\
\mathit{PrimaryExpression} & \rightarrow & \underline{\mathit{IntegerLiteral}} \\
 & | & \mathit{VarExpression} \\
 & | & \underline{\mathit{Operator}}\ \mathit{PrimaryExpression} \\
 & | & \mathbf{(}\ \mathit{Expression}\ \mathbf{)} \\
\mathit{VarExpression} & \rightarrow & \underline{\mathit{Identifier}}
\end{array}
$$

MiniTriangle Context-Free Syntax (3)

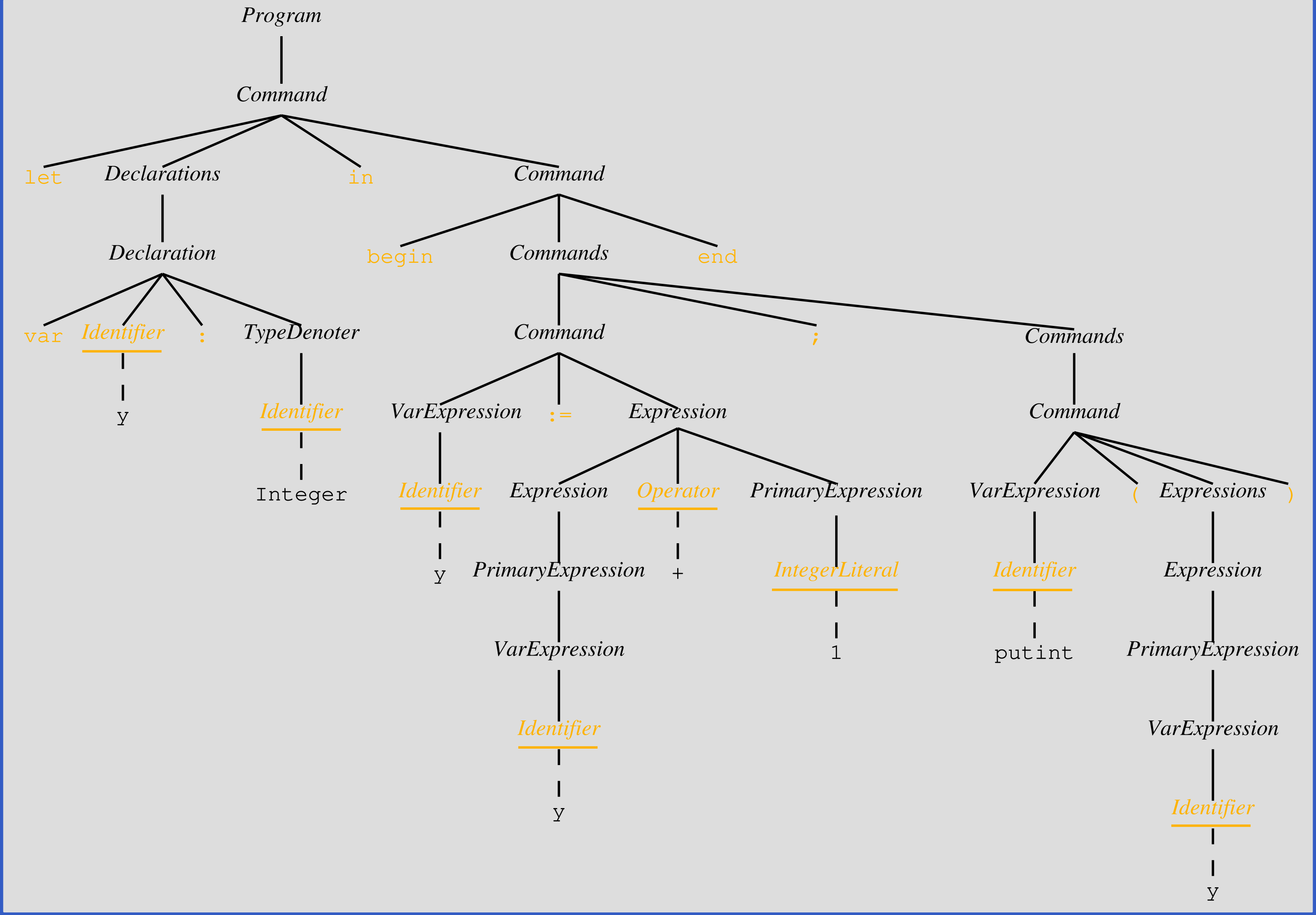
$$
\begin{array}{lcl}
\textit{Declarations} & \rightarrow & \textit{Declaration} \\
 & | & \textit{Declaration}\ \texttt{;}\ \textit{Declarations} \\
\textit{Declaration} & \rightarrow & \texttt{const}\ \underline{\textit{Identifier}}\ \texttt{:}\ \textit{TypeDenoter}\ \texttt{=}\ \textit{Expression} \\
 & | & \texttt{var}\ \underline{\textit{Identifier}}\ \texttt{:}\ \textit{TypeDenoter} \\
 & | & \texttt{var}\ \underline{\textit{Identifier}}\ \texttt{:}\ \textit{TypeDenoter}\ \texttt{:=}\ \textit{Expression} \\
\textit{TypeDenoter} & \rightarrow & \underline{\textit{Identifier}}
\end{array}
$$

Another MiniTriangle Program

The following is a ***syntactically*** valid MiniTriangle program (slightly changed from earlier to save some space):

```
let
    var y: Integer
in
    begin
        y := y + 1;
        putint(y)
    end
```

Parse Tree for the Program



Why a Lexical Grammar? (1)

Together, the lexical grammar and the context-free grammar specify the ***concrete syntax***.

In our case, both grammars are expressed in (E)BNF and looks similar.

So . . .

- Why not join them?
- Why not do away with scanning, and just do parsing?

Why a Lexical Grammar? (2)

Answer:

- ***Simplicity***: dealing with white space and comments in the context free grammar becomes extremely complicated. (Try it!)
- ***Efficiency***:
  - Working on classified groups of characters (tokens) facilitates parsing: may be possible to use a simpler parsing algorithm.
  - Grouping and classifying characters by as simple means as possible increases efficiency.

MiniTriangle Abstract Syntax (1)

This grammar specifies the ***phrase structure*** of MiniTriangle. In addition, it gives node labels to be used when drawing Abstract Syntax Trees.

$Program$	$\rightarrow$	$Command$	Program
$Command$	$\rightarrow$	$Expression$ `:=` $Expression$	CmdAssign
	$\mid$	$Expression$ `(` $Expression^*$ `)`	CmdCall
	$\mid$	$Command^*$	CmdSeq
	$\mid$	**`if`** $Expression$ **`then`** $Command$ **`else`** $Command$	CmdIf
	$\mid$	**`while`** $Expression$ **`do`** $Command$	CmdWhile
	$\mid$	**`let`** $Declaration^*$ **`in`** $Command$	CmdLet

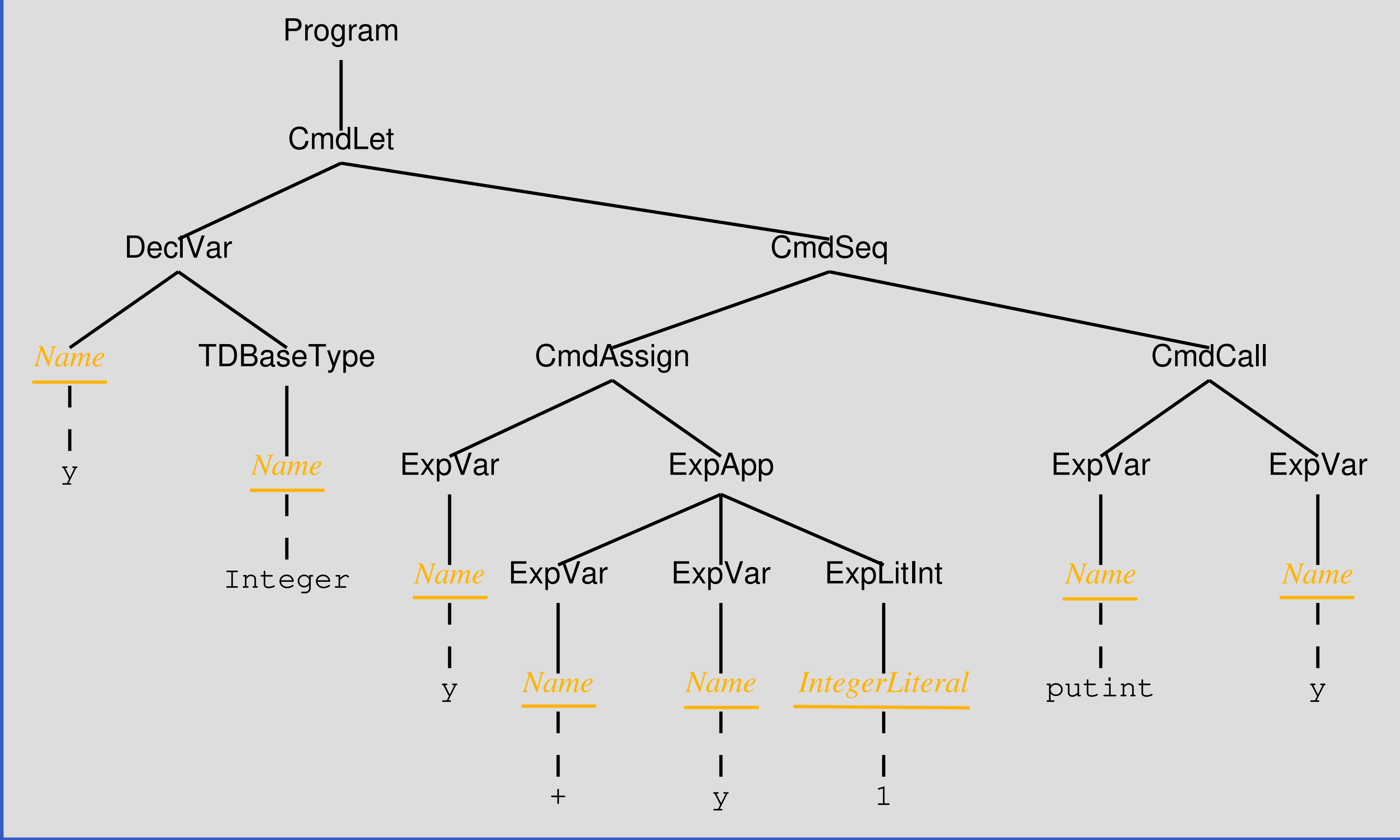
MiniTriangle Abstract Syntax (2)

$\mathit{Expression}$	$\rightarrow$	$\underline{\mathit{IntegerLiteral}}$	ExpLitInt
	$\mid$	$\underline{\mathit{Name}}$	ExpVar
	$\mid$	$\mathit{Expression}$ `(` $\mathit{Expression}^{*}$ `)`	ExpApp
$\mathit{Declaration}$	$\rightarrow$	**`const`** $\underline{\mathit{Name}}$ `:` $\mathit{TypeDenoter}$	DeclConst
		`=` $\mathit{Expression}$	
	$\mid$	**`var`** $\underline{\mathit{Name}}$ `:` $\mathit{TypeDenoter}$	DeclVar
		(`:=` $\mathit{Expression}$ $\mid$ ϵ)	
$\mathit{TypeDenoter}$	$\rightarrow$	$\underline{\mathit{Name}}$	TDBaseType

Note: Keywords and other fixed-spelling terminals serve only to make the connection with the concrete syntax clear.

$\underline{\mathit{Identifier}} \subseteq \underline{\mathit{Name}}$, $\underline{\mathit{Operator}} \subseteq \underline{\mathit{Name}}$

Abstract Syntax Tree for the Program



Note: ***fixed-spelling*** terminals are ***omitted*** because they are implied by the node labels.

Concrete vs. Abstract Syntax

Key points:

- Concrete syntax (for our purposes): ***string*** (generated from the lexical and context-free grammars)
- Abstract syntax: ***tree***

Concrete AST Representation

Mapping of abstract syntax to algebraic datatypes

- Each non-terminal is mapped to a ***type***.
- Each label is mapped to a ***constructor*** for the corresponding type.
- The constructors get one argument for each non-terminal and “variable” terminal in the RHS of the production.
- Sequences are represented by lists.
- Options are represented by values of type `Maybe`.
- “Literal” terminals are ignored.

Concrete AST Representation (2)

```
data Command
   = CmdAssign Expression Expression
   | CmdCall Expression [Expression]
   | CmdSeq [Command]
   | CmdIf Expression Command Command
   | CmdWhile Expression Command
   | CmdLet [Declaration] Command
```

Concrete AST Representation (3)

```
data Expression
  = ExpLitInt Integer
  | ExpVar Name
  | ExpApp Expression [Expression]

data Declaration
  = DeclConst Name TypeDenoter Expression
  | DeclVar Name TypeDenoter (Maybe Expression)
```

Concrete AST Representation (4)

In fact, the lab code uses labelled fields:

```
data Command
    = CmdAssign {
          caVar     :: Expression,
          caVal     :: Expression,
          cmdSrcPos :: SrcPos
      }
    | CmdCall {
          ccProc    :: Expression,
          ccArgs    :: [Expression],
          cmdSrcPos :: SrcPos
      }
      ...
```

Haskell Representation of the Program

```
CmdLet
     (DeclVar "y" (TDBaseName "Integer") Nothing)
     (CmdSeq [CmdAssign (ExpVar "y")
                        (ExpApp (ExpVar "+")
                                [ExpVar "y",
                                 ExpLitInt 1]),
              CmdCall (ExpVar "putint")
                      [ExpVar "y"]])
```

Assumption:

```
type Name = String
```