COMP3012/G53CMP: Lecture 2

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)

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    - Usually ***strings*** of characters or symbols.
    - Some languages have graphical syntax.
  - ***Abstract Syntax***: ***trees*** representing the essential structure of syntactically valid programs.

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  - ***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***.

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- Language definitions (aka ***specifications***) can be ***formal*** or ***informal***. Usually they are somewhere in between.

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- 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***.

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- the ***Object Language***: the language being defined
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Moreover, the semantics of the meta language must be well understood!

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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: `http://java.sun.com/docs/books/jls` (See e.g. Third Edition, Section 14.9.)

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- ***inference rules and logic*** for specifying static and/or dynamic semantics
- ***denotational semantics*** for specifying dynamic semantics.

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- 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***.

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  - Start symbol usually called S.

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    - terminals with ***variable spelling*** and special symbols are written like $\underline{\mathit{this}}$

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    - terminals are written like **`this`**
    - terminals with ***variable spelling*** and special symbols are written like *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***).

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- 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

The following EBNF grammar

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

(where $Decl$ and $Stmt$ are defined elsewhere)

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

$$\begin{aligned} Block &\rightarrow \texttt{begin}\; BlockRec\; \texttt{end} \\ BlockRec &\rightarrow \epsilon \mid BlockRec\; BlockAlts \\ BlockAlts &\rightarrow Decl \mid Stmt \end{aligned}$$

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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
```

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  - ***language symbols*** or ***tokens***
  - ***white space***
  - ***comments***
- The ***Context-Free syntax***.

MiniTriangle Lexical Syntax (1)

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

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- 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:

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

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  Keyword $\rightarrow$ `b e g i n` | `c o n s t` | ...

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

MiniTriangle: Tokens

Some valid MiniTriangle tokens:

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- `const` (Keyword)
- `42` (Integer-Literal)
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A: An implicit "***maximal munch rule***" used to disambiguate!

MiniTriangle Context-Free Syntax (1)

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

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

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}}
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MiniTriangle Context-Free Syntax (3)

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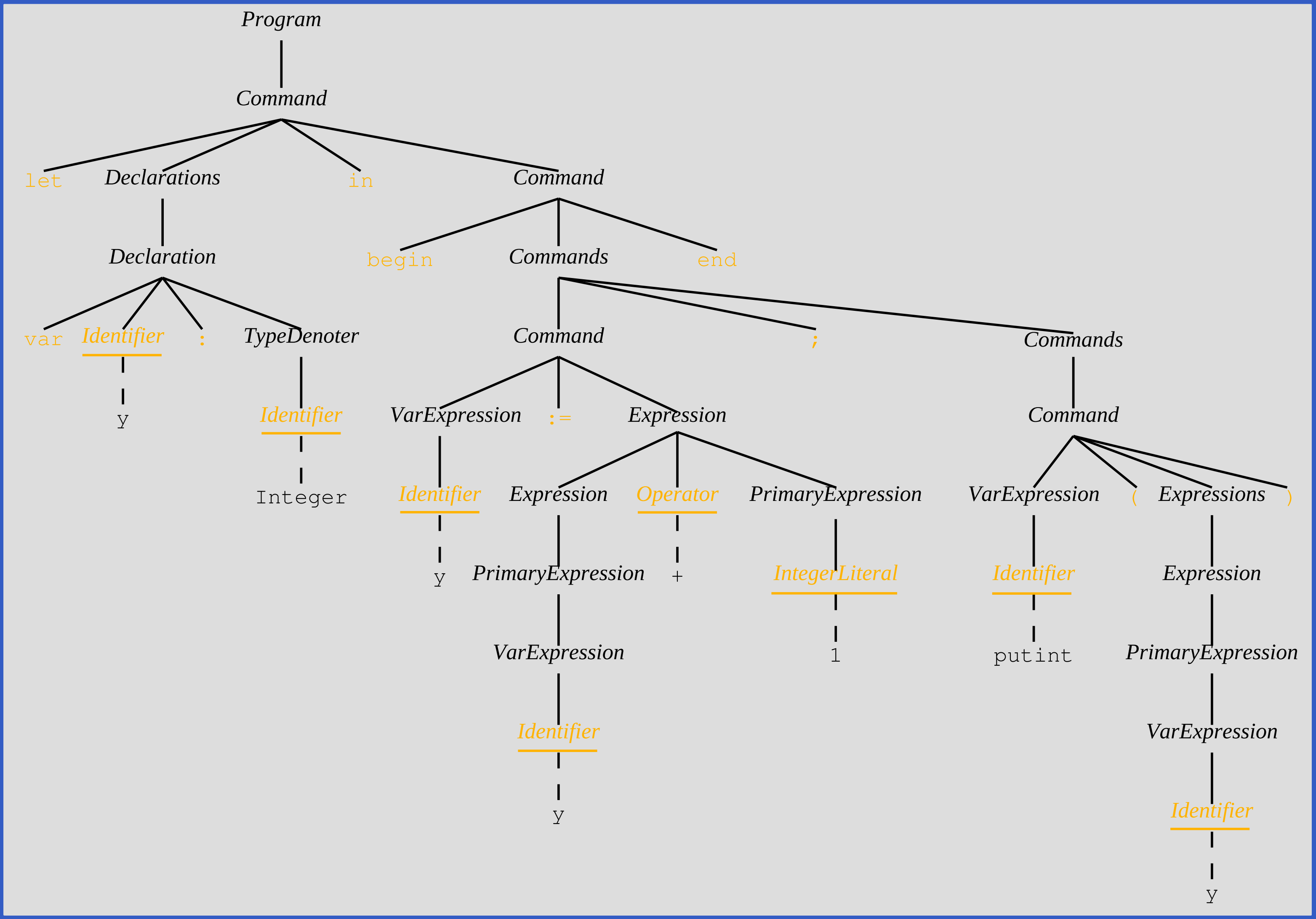
\begin{array}{lcl}
\mathit{Declarations} & \rightarrow & \mathit{Declaration} \\
 & | & \mathit{Declaration}\ \texttt{;}\ \mathit{Declarations} \\
\mathit{Declaration} & \rightarrow & \texttt{const}\ \underline{\mathit{Identifier}}\ \texttt{:}\ \mathit{TypeDenoter}\ \texttt{=}\ \mathit{Expression} \\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



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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!)

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- ***Efficiency***:
  - Working on classified groups of characters (tokens) facilitates parsing: may be possible to use a simpler parsing algorithm.

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- ***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.

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

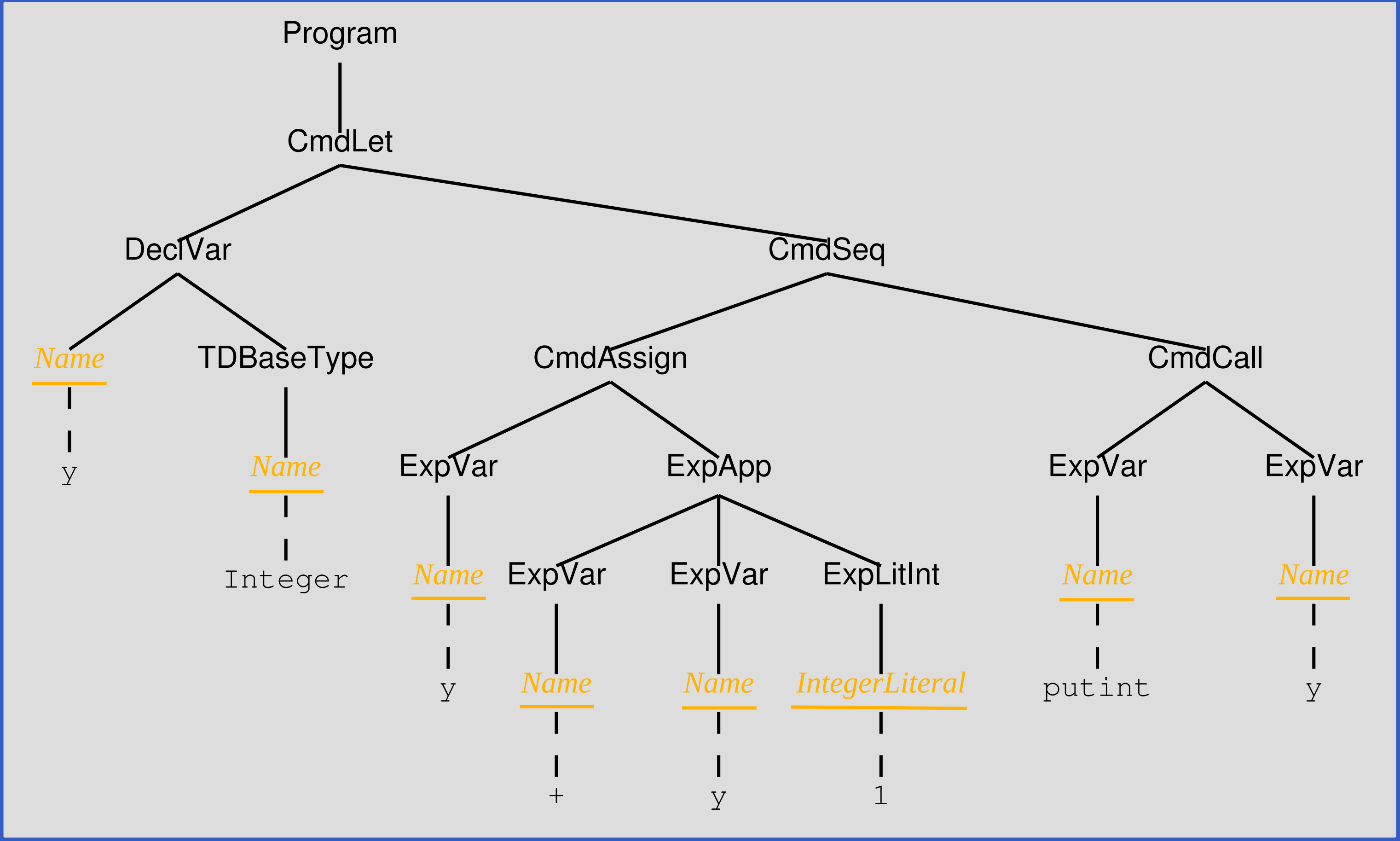
MiniTriangle Abstract Syntax (2)

Expression	$\rightarrow$	*IntegerLiteral*	ExpLitInt
	$\vert$	*Name*	ExpVar
	$\vert$	*Expression* **(** *Expression** **)**	ExpApp
Declaration	$\rightarrow$	**const** *Name* **:** *TypeDenoter* **=** *Expression*	DeclConst
	$\vert$	**var** *Name* **:** *TypeDenoter* (**:=** *Expression* $\vert$ ϵ)	DeclVar
TypeDenoter	$\rightarrow$	*Name*	TDBaseType

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

Identifier $\subseteq$ *Name*, *Operator* $\subseteq$ *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: ***string*** (generated from the lexical and context-free grammars)
- Abstract syntax: ***tree***

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(Ways to describe ***graphical*** concrete syntax are more varied.)

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Mapping of abstract syntax to algebraic datatypes

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- Options are represented by values of type `Maybe`.

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- 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
```