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
- the ***Meta Language***: the language of the definition itself.

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 are written like **`this`**
    - terminals with ***variable spelling*** and special symbols are written like <u>*this*</u>

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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:

$$AssignStmt \rightarrow \underline{Identifier}\ \texttt{:=}\ Expr$$

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

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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)

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

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- Note! Each individual character of a terminal is actually a terminal symbol! I.e., really:

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- Special characters are written like *this*.
  Note! They are single terminal symbols!

MiniTriangle: Tokens

Some valid MiniTriangle tokens:

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- `42` (Integer-Literal)
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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)

Expressions	$\rightarrow$	*Expression*
	$\mid$	*Expression* , *Expressions*
Expression	$\rightarrow$	*PrimaryExpression*
	$\mid$	*Expression* <u>*Operator*</u> *PrimaryExpression*
PrimaryExpression	$\rightarrow$	<u>*IntegerLiteral*</u>
	$\mid$	*VarExpression*
	$\mid$	<u>*Operator*</u> *PrimaryExpression*
	$\mid$	(*Expression*)
VarExpression	$\rightarrow$	<u>*Identifier*</u>

MiniTriangle Context-Free Syntax (3)

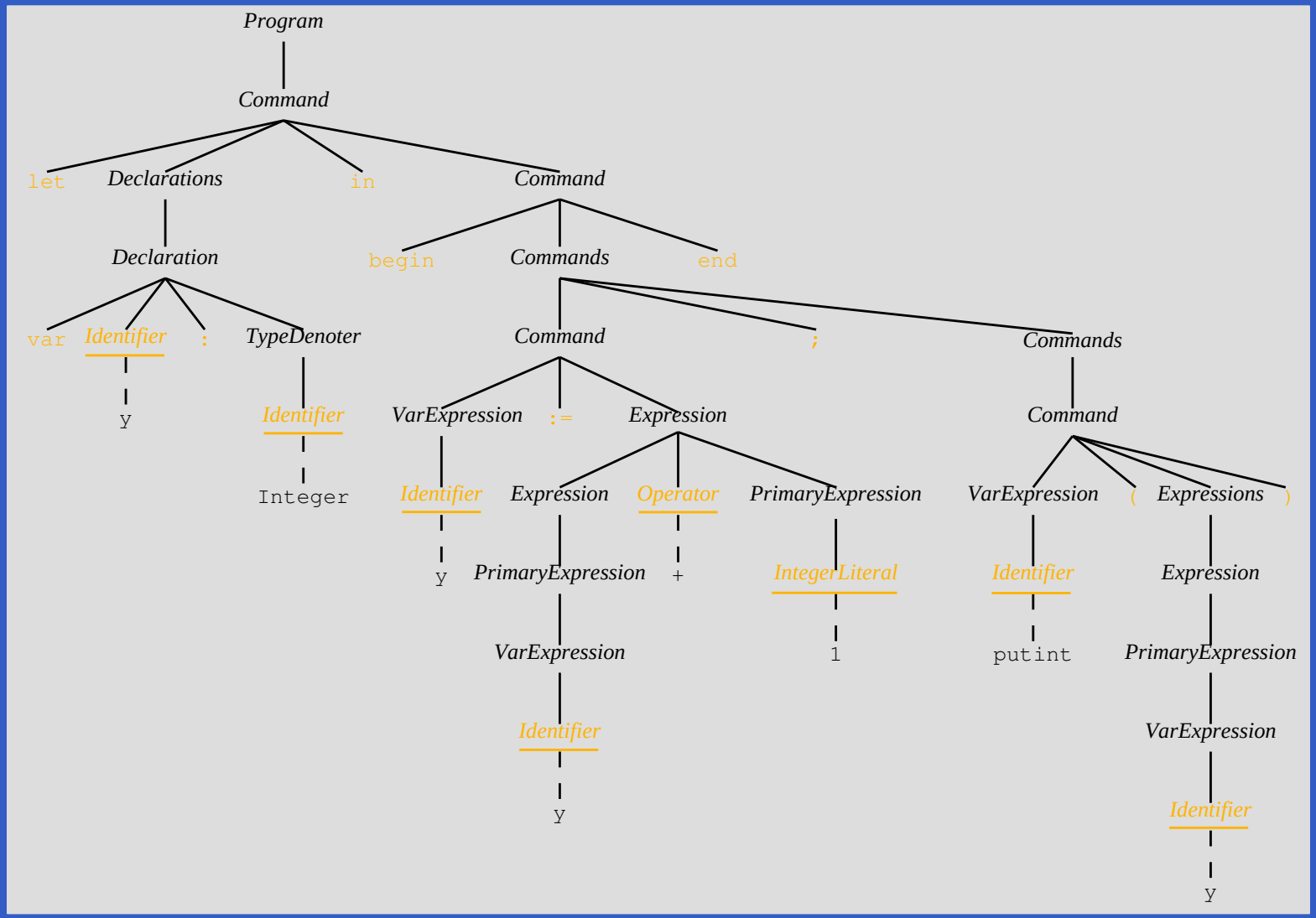
$$
\begin{array}{lcl}
\mathit{Declarations} & \rightarrow & \mathit{Declaration} \\
 & | & \mathit{Declaration}\ \texttt{;}\ \mathit{Declarations} \\
\mathit{Declaration} & \rightarrow & \texttt{const}\ \underline{\mathit{Identifier}}\ \texttt{:}\ \mathit{TypeDenoter}\ \texttt{=}\ \mathit{Expression}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

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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- ***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

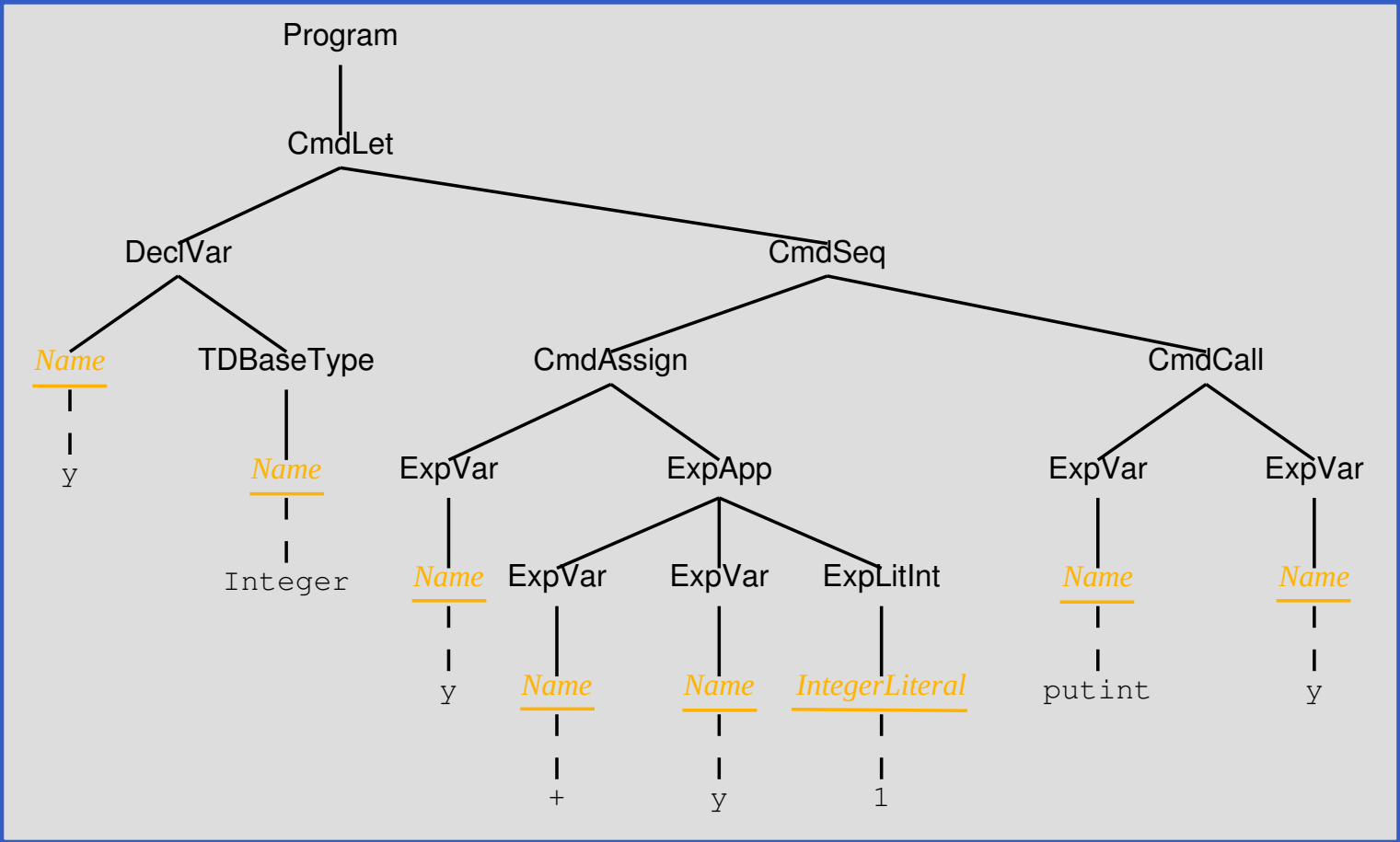
MiniTriangle Abstract Syntax (2)

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