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)

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

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*** (or "G52LAC 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 *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***).

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

The following EBNF grammar

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

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

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

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)

Program → (*Token* | *Separator*)*

Token → *Keyword* | *Identifier* | *IntegerLiteral* | *Operator*
  | `,` | `;` | `:` | `:=` | `=` | `(` | `)` | *eot*

Keyword → `begin` | `const` | `do` | `else` | `end` | `if` | `in`
  | `let` | `then` | `var` | `while`

Identifier → *Letter* | *Identifier Letter* | *Identifier Digit*
  except *Keyword*

IntegerLiteral → *Digit* | *IntegerLiteral Digit*

Operator → `+` | `-` | `*` | `/` | `<` | `<=` | `==` | `!=` | `>=` | `>` | `&&` | `||` | `!`

Separator → *Comment* | *space* | *eol*

Comment → `//` (any character except *eol*)* *eol*

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:

  Keyword → `b e g i n` | `c o n s t` | . . .
- Special characters are written like *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.)

Program → *Command*

Commands → *Command*
  | *Command* `;` *Commands*

Command → *VarExpression* `:=` *Expression*
  | *VarExpression* `(` *Expressions* `)`
  | `if` *Expression* `then` *Command* `else` *Command*
  | `while` *Expression* `do` *Command*
  | `let` *Declarations* `in` *Command*
  | `begin` *Commands* `end`

MiniTriangle Context-Free Syntax (2)

Expressions → *Expression*
  | *Expression* `,` *Expressions*

Expression → *PrimaryExpression*
  | *Expression* *Operator* *PrimaryExpression*

PrimaryExpression → *IntegerLiteral*
  | *VarExpression*
  | *Operator* *PrimaryExpression*
  | `(` *Expression* `)`

VarExpression → *Identifier*

MiniTriangle Context-Free Syntax (3)

Declarations → *Declaration*
  | *Declaration* `;` *Declarations*

Declaration → `const` *Identifier* `:` *TypeDenoter* `=` *Expression*
  | `var` *Identifier* `:` *TypeDenoter*
  | `var` *Identifier* `:` *TypeDenoter* `:=` *Expression*

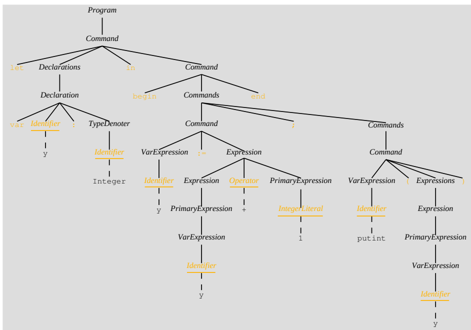
TypeDenoter → *Identifier*

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	→	*Command*	Program
Command	→	*Expression* `:=` *Expression*	CmdAssign
	|	*Expression* `(` *Expression** `)`	CmdCall
	|	*Command**	CmdSeq
	|	**if** *Expression* **then** *Command* **else** *Command*	CmdIf
	|	**while** *Expression* **do** *Command*	CmdWhile
	|	**let** *Declaration** **in** *Command*	CmdLet

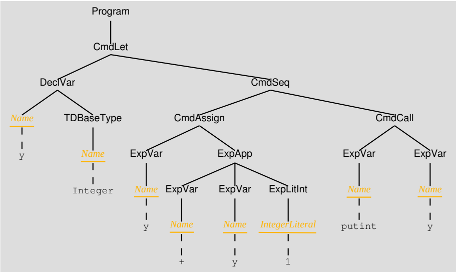
MiniTriangle Abstract Syntax (2)

Expression	→	<u>*IntegerLiteral*</u>	ExpLitInt
	|	<u>*Name*</u>	ExpVar
	|	*Expression* `(` *Expression** `)`	ExpApp
Declaration	→	**const** <u>*Name*</u> `:` *TypeDenoter* `=` *Expression*	DeclConst
	|	**var** <u>*Name*</u> `:` *TypeDenoter* (`:=` *Expression* | ϵ)	DeclVar
TypeDenoter	→	<u>*Name*</u>	TDBaseType

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

<u>*Identifier*</u> $\subseteq$ <u>*Name*</u>, <u>*Operator*</u> $\subseteq$ <u>*Name*</u>

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***

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

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
```