G54FOP: Lecture 1

Basic Formal Language Notions and Abstract Syntax

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About These Slides

We give a brief recap on some central notions from the theory of formal languages, covered in a typical undergraduate course on that topic such as G52MAL, before moving on to abstract syntax.

To recap, consult the G52MAL lecture notes:

> **`http://www.cs.nott.ac.uk/~nhn/G52MAL`**

or a book on the topic, such as

> John E. Hopcroft, Rajeev Motwani, Jeffrey D. Ullman. *Introduction to Automata Theory, Languages, and Computation, 2nd edition*, Addison Wesley, 2001.

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- ***Syntax***: the ***form*** of programs
  - ***Concrete Syntax*** (or ***Surface Syntax***): (typically) the exact character sequences that are syntactically valid programs.
  - ***Abstract Syntax***: the essential structure of syntactically valid programs.

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

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- A large part of this module will thus be concerned with various aspects of syntax and semantics for programming languages.
- We will start by looking at syntax, recapitulating some notions from the theory of formal languages related to ***concrete syntax***, and then move on to ***abstract syntax***.

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The term ***string*** is often used interchangeably with the term ***word***.

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ϵ, the empty word, is ***never*** a symbol of an alphabet.

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words	?

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Note the distinction between ϵ, $\emptyset$, and $\{\epsilon\}$!

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- What about the set of all natural numbers smaller than some given number n?
- Homework:
  - Suggest an alphabet of a handful of ***drink ingredients***.
  - List some words over your alphabet.
  - Does all possible words describe “interesting” drinks?
  - Define a language of interesting drinks.

All Words over an Alphabet (1)

Given an alphabet Σ we define the set Σ^* as set of words (or sequences) over Σ:

- The empty word $\epsilon \in \Sigma^*$.
- given a symbol $x \in \Sigma$ and a word $w \in \Sigma^*$, $xw \in \Sigma^*$.
- These are all elements in Σ^*.

This is called an ***inductive definition***.

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Inductive definitions and reasoning by induction over inductively defined structures will be recurring themes in this module.

All Words over an Alphabet (2)

Example: Given $\Sigma = \{0, 1\}$, some elements of Σ^* are

- ϵ (the empty word)
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- 00, 10, 01, 11
- 000, 100, 010, 110, 001, 101, 011, 111
- $\ldots$

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Note: although there are infinitely many words in Σ^*, each word has a ***finite*** length!

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- $L \in \mathcal{P}(\Sigma^*)$.

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- The set of words that contain the same number of 0s and 1s is a language over $\Sigma = \{0, 1\}$. (Finite or infinite?)
- The set of correct Java programs. This is a language over the set of UNICODE characters.

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- The CFLs captures ideas common in programming languages such as
  - nested structure
  - balanced parentheses
  - matching keywords like `begin` and `end`.
- Most "reasonable" CFLs can be recognised by a fairly simple machine: a ***deterministic pushdown automaton***.

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- allows context-free constraints to be expressed
- imparts a hierarchical structure to the words in the language
- allows simple and efficient ***parsing***:
  - determining if a word belongs to the language
  - determining its ***phrase structure*** if so.

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- S, the ***start symbol***, is a distinguished element of N
- P is a finite set of ***productions***, written $A \rightarrow \alpha$, where $A \in N$ and $\alpha \in (N \cup T)^*$

Context-Free Grammar: Example

$$G = (\{S, A\}, \{a, b\}, P, S)$$

where P consists of the productions

$$\begin{aligned} S &\rightarrow \epsilon \\ S &\rightarrow aA \\ A &\rightarrow bS \end{aligned}$$

Context-Free Grammars: Notation

- Productions with the same LHS are usually grouped together. For example, the productions for S from the previous example:

$$S \longrightarrow \epsilon \mid aA$$

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- Another common way of writing productions is

  $$A ::= \alpha$$

The Directly Derives Relation (1)

To formally define the language generated by

$$G = (N, T, P, S)$$

we first define a binary relation $\underset{G}{\Rightarrow}$ on strings over $N \cup T$, read "***directly derives*** in grammar G", being the least relation such that

$$\alpha A \gamma \underset{G}{\Rightarrow} \alpha \beta \gamma$$

whenever $A \to \beta$ is a production in G.

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whenever $A \rightarrow \beta$ is a production in G.

Note: a production can be applied regardless of context, hence ***context-free***.

The Directly Derives Relation (2)

When it is clear which grammar G is involved, we use $\Rightarrow$ instead of $\underset{G}{\Rightarrow}$.

Example: Given the grammar

$$\begin{array}{rcl} S & \rightarrow & \epsilon \mid aA \\ A & \rightarrow & bS \end{array}$$

we have

$$\begin{array}{rclcrcl} S & \Rightarrow & \epsilon & \quad & aA & \Rightarrow & abS \\ S & \Rightarrow & aA & \quad & SaAaa & \Rightarrow & SabSaa \end{array}$$

The Derives Relation (1)

The relation $\overset{*}{\underset{G}{\Rightarrow}}$, read "***derives*** in grammar G", is the reflexive, transitive closure of $\underset{G}{\Rightarrow}$.

That is, $\overset{*}{\underset{G}{\Rightarrow}}$ is the least relation on strings over $N \cup T$ such that:

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- $\alpha \overset{*}{\underset{G}{\Rightarrow}} \alpha$ (reflexive)
- $\alpha \overset{*}{\underset{G}{\Rightarrow}} \beta$ if $\alpha \overset{*}{\underset{G}{\Rightarrow}} \gamma \wedge \gamma \overset{*}{\underset{G}{\Rightarrow}} \beta$ (transitive)

The Derives Relation (2)

Again, we use $\stackrel{*}{\Rightarrow}$ instead of $\underset{G}{\stackrel{*}{\Rightarrow}}$ when G is obvious.

Example: Given the grammar

$$\begin{array}{rcl} S & \rightarrow & \epsilon \mid aA \\ A & \rightarrow & bS \end{array}$$

we have

$$\begin{array}{rcl} S & \stackrel{*}{\Rightarrow} & \epsilon \\ S & \stackrel{*}{\Rightarrow} & aA \\ aA & \stackrel{*}{\Rightarrow} & abS \end{array} \qquad \begin{array}{rcl} S & \stackrel{*}{\Rightarrow} & abS \\ S & \stackrel{*}{\Rightarrow} & ababS \\ S & \stackrel{*}{\Rightarrow} & abab \end{array}$$

Language Generated by a Grammar

The language generated by a context-free grammar

$$G = (N, T, P, S)$$

denoted $L(G)$, is defined as follows:

$$L(G) = \{w \mid w \in T^* \ \wedge \ S \overset{*}{\underset{G}{\Rightarrow}} w\}$$

A language L is a ***Context-Free Language*** (CFL) iff $L = L(G)$ for some CFG G.

A string $\alpha \in (N \cup T)^*$ is a ***sentential form*** iff $S \overset{*}{\Rightarrow} \alpha$.

Language Generation: Example

Given the grammar
$G = (N = \{S, A\}, T = \{a, b\}, P, S)$ where P are the productions

$$\begin{aligned} S &\rightarrow \epsilon \mid aA \\ A &\rightarrow bS \end{aligned}$$

we have

$$\begin{aligned} L(G) &= \{(ab)^i \mid i \geq 0\} \\ &= \{\epsilon, ab, abab, ababab, abababab, \ldots\} \end{aligned}$$

Example: MiniTriangle CFG (1)

Concrete syntax for MiniTriangle:

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

Example: MiniTriangle CFG (2)

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

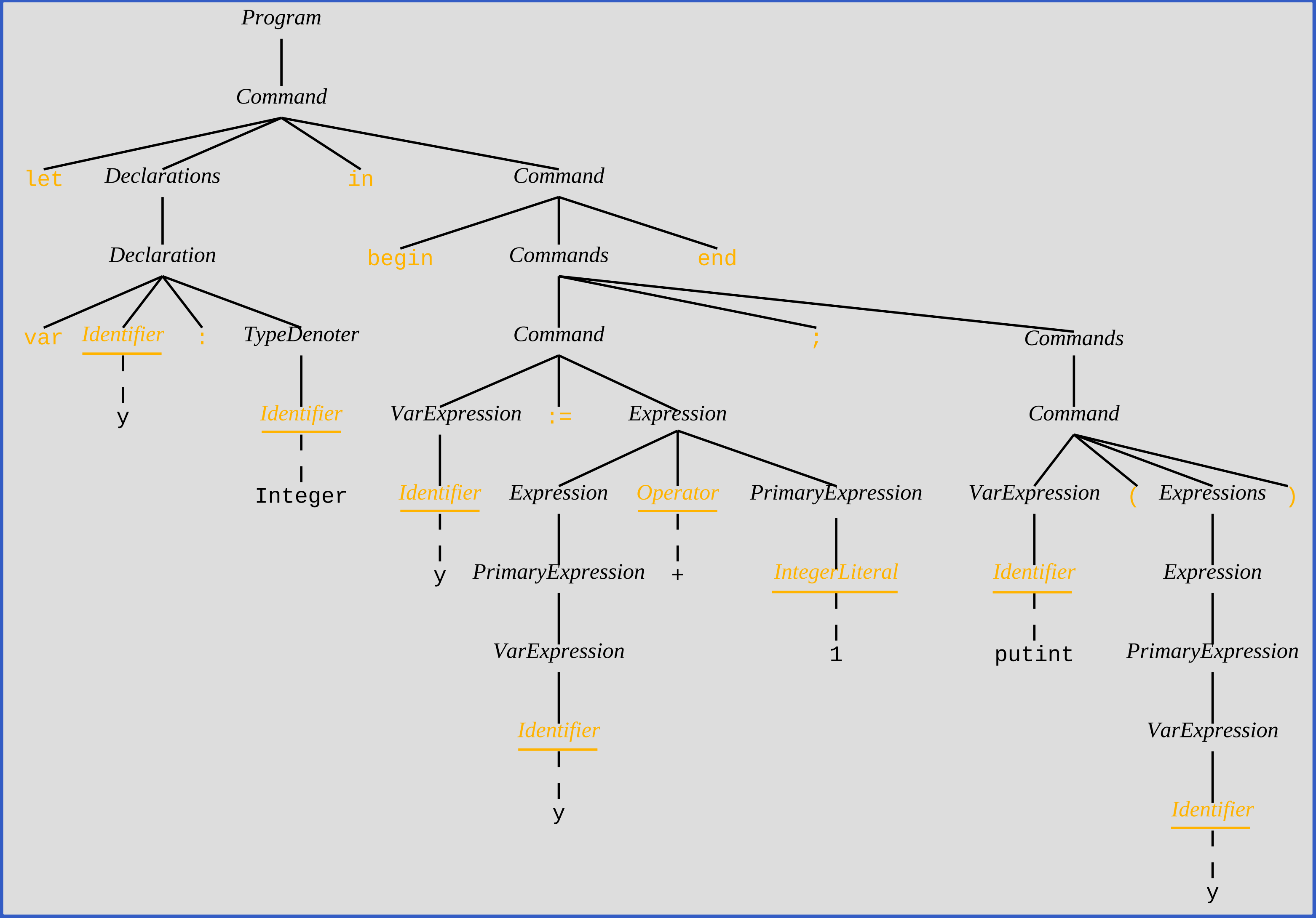
Example: MiniTriangle CFG (3)

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

A MiniTriangle Program

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

Parse Tree for the Program



MiniTriangle Abstract Syntax (1)

The details of the concrete syntax often obscure the essence of the structure of a program. In contrast, ***abstract syntax*** describe this directly:

$Program$	$\rightarrow$	$Command$	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

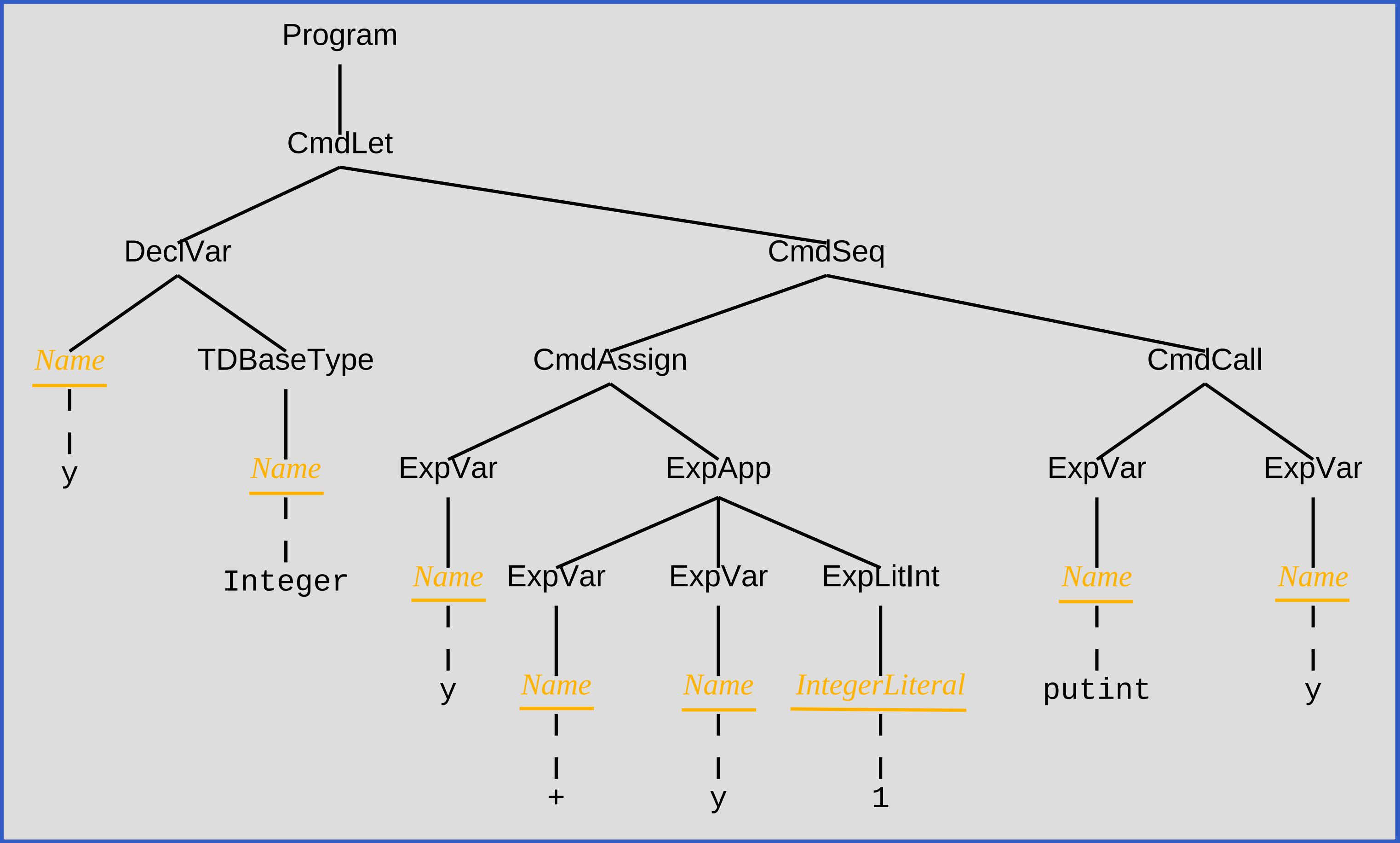
MiniTriangle Abstract Syntax (2)

Expression	$\rightarrow$	<u>*IntegerLiteral*</u>	ExpLitInt
	|	<u>*Name*</u>	ExpVar
	|	*Expression* **(** *Expression** **)**	ExpApp
Declaration	$\rightarrow$	**const** <u>*Name*</u> **:** *TypeDenoter*	DeclConst
		= *Expression*	
	|	**var** <u>*Name*</u> **:** *TypeDenoter*	DeclVar
		(**:=** *Expression* | ϵ)	
TypeDenoter	$\rightarrow$	<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



Key Point: The abstract syntax specifies ***trees***, not strings.