

Declarative Computation Model

Defining practical programming languages (VRH2.1)

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Programming

- A computation model: describes a language and how the sentences (expressions, statements) of the language are executed by an abstract machine
- A set of programming techniques: to express solutions to the problems you want to solve
- A set of reasoning techniques: to reason about programs to increase the confidence that they behave correctly and to calculate their efficiency

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Declarative Programming Model

- Guarantees that the computations are evaluating functions on (partial) data structures
- The core of functional programming (LISP, Scheme, ML, Haskell)
- The core of logic programming (Prolog, Mercury)
- Stateless programming vs. stateful (imperative) programming
- We will see how declarative programming underlies concurrent and object-oriented programming (Erlang, C++, Java, SALSA)

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Defining a programming language

- Syntax (grammar)
- Semantics (meaning)

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Language syntax

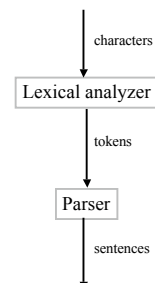
- Defines what are the legal programs, i.e. programs that can be executed by a machine (interpreter)
- Syntax is defined by grammar rules
- A grammar defines how to make 'sentences' out of 'words'
- For programming languages: sentences are called statements (commands, expressions)
- For programming languages: words are called tokens
- Grammar rules are used to describe both tokens and statements

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Language syntax (2)

- A *statement* is a sequence of tokens
- A *token* is a sequence of characters
- A program that recognizes a sequence of characters and produces a sequence of tokens is called a *lexical analyzer*
- A program that recognizes a sequence of tokens and produces a statement representation is called a *parser*
- Normally statements are represented as (parse) *trees*



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Extended Backus-Naur Form

- EBNF (Extended Backus-Naur Form) is a common notation to define grammars for programming languages
- Terminal symbols and non-terminal symbols
- *Terminal symbol* is a token
- *Nonterminal symbol* is a sequence of tokens, and is represented by a grammar rule
 $\langle \text{nonterminal} \rangle ::= \langle \text{rule body} \rangle$

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Grammar rules

- $\langle \text{digit} \rangle ::= 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$
- $\langle \text{digit} \rangle$ is defined to represent one of the ten tokens 0, 1, ..., 9
- The symbol ' \mid ' is read as 'or'
- Another reading is that $\langle \text{digit} \rangle$ describes the set of tokens {0, 1, ..., 9}
- Grammar rules may refer to other nonterminals
- $\langle \text{integer} \rangle ::= \langle \text{digit} \rangle \{ \langle \text{digit} \rangle \}$
- $\langle \text{integer} \rangle$ is defined as the sequence of a $\langle \text{digit} \rangle$ followed by zero or more $\langle \text{digit} \rangle$'s

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How to read grammar rules

- $\langle x \rangle$: is a **nonterminal** x
- $\langle x \rangle ::= \text{Body}$: $\langle x \rangle$ is defined by *Body*
- $\langle x \rangle \mid \langle y \rangle$: **either** $\langle x \rangle$ **or** $\langle y \rangle$ (choice)
- $\langle x \rangle \langle y \rangle$: the sequence $\langle x \rangle$ followed by $\langle y \rangle$
- $\{ \langle x \rangle \}$: a sequence of zero or more occurrences of $\langle x \rangle$
- $\{ \langle x \rangle \}^*$: a sequence of one or more occurrences of $\langle x \rangle$
- $[\langle x \rangle]$: zero or one occurrences of $\langle x \rangle$
- Read the grammar rule from left to right to give the following sequence:
 - Each terminal symbol is added to the sequence
 - Each nonterminal is replaced by its definition
 - For each $\langle x \rangle \mid \langle y \rangle$ pick any of the alternatives
 - For each $\langle x \rangle \langle y \rangle$ add the sequence $\langle x \rangle$ followed by the sequence $\langle y \rangle$

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Context-free and context-sensitive grammars

- Grammar rules can be used either
 - to verify that a statement is legal, or
 - to generate all possible statements
- The set of all possible statements generated from a grammar and one nonterminal symbol is called a *(formal) language*
- EBNF notation defines a class of grammars called *context-free* grammars
- Expansion of a nonterminal is always the same regardless of where it is used
- For practical languages, a context-free grammar is not enough, usually a condition on the context is sometimes added

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Context-free and context-sensitive grammars

- It is easy to read and understand
- Defines a superset of the language
- Expresses restrictions imposed by the language (e.g. variable must be declared before use)
- Makes the grammar rules context sensitive

Context-free grammar
(e.g. with EBNF)

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Set of extra conditions

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Examples

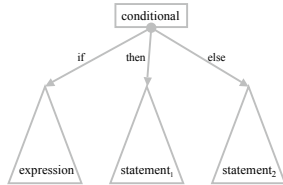
- $\langle \text{statement} \rangle ::= \text{skip} \mid \langle \text{expression} \rangle '=' \langle \text{expression} \rangle \mid \dots$
- $\langle \text{expression} \rangle ::= \langle \text{variable} \rangle \mid \langle \text{integer} \rangle \mid \dots$
- $\langle \text{statement} \rangle ::= \text{if } \langle \text{expression} \rangle \text{ then } \langle \text{statement} \rangle$
 $\quad \{ \text{elseif } \langle \text{expression} \rangle \text{ then } \langle \text{statement} \rangle \}$
 $\quad [\text{else } \langle \text{statement} \rangle] \text{ end } \mid \dots$

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Example: (Parse Trees)

- `if (expression) then (statement)1 else (statement)2 end`



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Language Semantics

- Semantics defines what a program does when it executes
- Semantics should be simple and yet allows reasoning about programs (correctness, execution time, and memory use)
- How can this be achieved for a practical language that is used to build complex systems (millions of lines of code)?
- The *kernel language* approach

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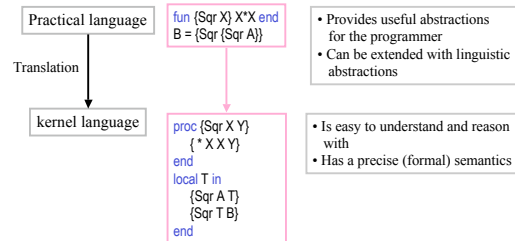
Kernel Language Approach

- Define a very simple language (kernel language)
- Define the computation model of the kernel language
- By defining how the constructs (statements) of the language manipulate (create and transform) the data structures (the entities) of the language
- Define a mapping scheme (translation) of the full programming language into the kernel language
- Two kinds of translations: linguistic abstractions and syntactic sugar

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Kernel Language Approach



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Linguistic abstractions vs. syntactic sugar

- Linguistic abstractions, provide higher level concepts that the programmer can use to model and reason about programs (systems)
- Examples: functions (`fun`), iterations (`for`), classes and objects (`class`), mailboxes (`receive`)
- The functions (calls) are translated to procedures (calls)
- The translation answers questions about the function call: `{F1 {F2 X} {F3 X}}`

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Linguistic abstractions vs. syntactic sugar

- Linguistic abstractions, provide higher level concepts that the programmer can use to model and reason about programs (systems)
- Syntactic sugar are short cuts and conveniences to improve readability

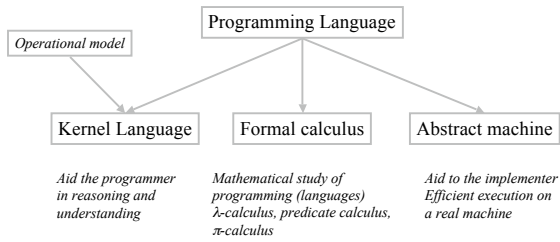
```
if N==1 then [1]
else
  local L in
    ...
  end
end
```

```
if N==1 then [1]
else L in
  ...
end
```

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Approaches to semantics



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Exercises

39. Write a valid EBNF grammar for lists of non-negative integers in Oz.

40. Write a valid EBNF grammar for the λ -calculus.

- Which are terminal and which are non-terminal symbols?
- Draw the parse tree for the expression:

$((\lambda x.x \lambda y.y) \lambda z.z)$

41. *The grammar

$\langle \text{exp} \rangle ::= \langle \text{int} \rangle \mid \langle \text{exp} \rangle \langle \text{op} \rangle \langle \text{exp} \rangle$

$\langle \text{op} \rangle ::= + \mid *$

is ambiguous (e.g., it can produce two parse trees for the expression $2*3+4$). Rewrite the grammar so that it accepts the same language unambiguously.

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