Declarative Computation Model
Defining practical programming languages (CTM 2.1)

Carlos Varela
RPI

March 2, 2015

Adapted with permission from:
Seif Haridi
KTH
Peter Van Roy
UCL

Programming Concepts

- 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

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)

Defining a programming language

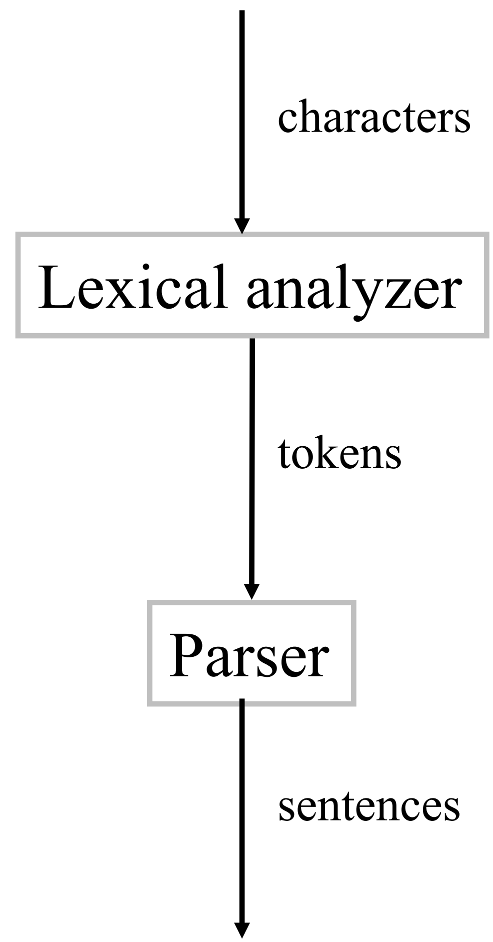
- Syntax (grammar)
- Semantics (meaning)

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

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*



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

  ⟨nonterminal⟩ ::= ⟨rule body⟩

Grammar rules

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

How to read grammar rules

- $\langle x \rangle$: is a nonterminal *x*
- $\langle x \rangle$ ::= *Body* : $\langle x \rangle$ is defined by *Body*
- $\langle x \rangle$ | $\langle y \rangle$: 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 $\langle x \rangle$ | $\langle y \rangle$ pick any of the alternatives
  - For each $\langle x \rangle$ $\langle y \rangle$ add the sequence $\langle x \rangle$ followed by the sequence $\langle y \rangle$

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

Context-free and context-sensitive grammars

- It is easy to read and understand
- Defines a superset of the language

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

+

- Expresses restrictions imposed by the language (e.g. variable must be declared before use)
- Makes the grammar rules context sensitive

Set of extra conditions

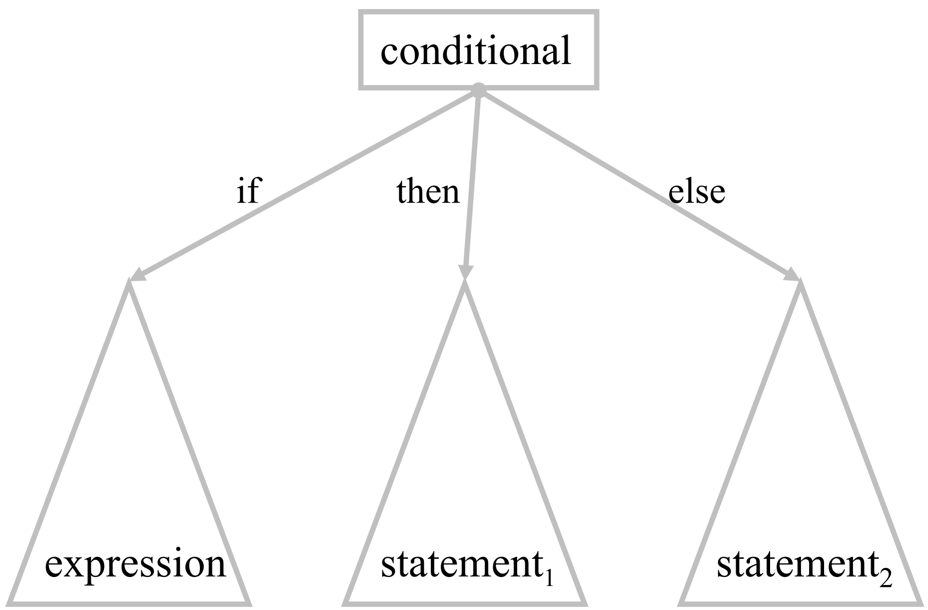
Examples

- ⟨statement⟩ **::=** skip **|** ⟨expression⟩ '= ' ⟨expression⟩ **|** …
- ⟨expression⟩ **::=** ⟨variable⟩ **|** ⟨integer⟩ **| …**

- ⟨statement⟩ **::=** if ⟨expression⟩ then ⟨statement⟩
  { elseif ⟨expression⟩ then ⟨statement⟩ **}**
  [else ⟨statement⟩ **]** end **| …**

Example: (Parse Trees)

- if ⟨expression⟩ then ⟨statement⟩$_1$ else ⟨statement⟩$_2$ end



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

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

Kernel Language Approach

Practical language

Translation

kernel language

```
fun {Sqr X} X*X end
B = {Sqr {Sqr A}}
```

```
proc {Sqr X Y}
   {* X X Y}
end
local T in
   {Sqr A T}
   {Sqr T B}
end
```

- Provides useful abstractions for the programmer
- Can be extended with linguistic abstractions

- Is easy to understand and reason with
- Has a precise (formal) semantics

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}}

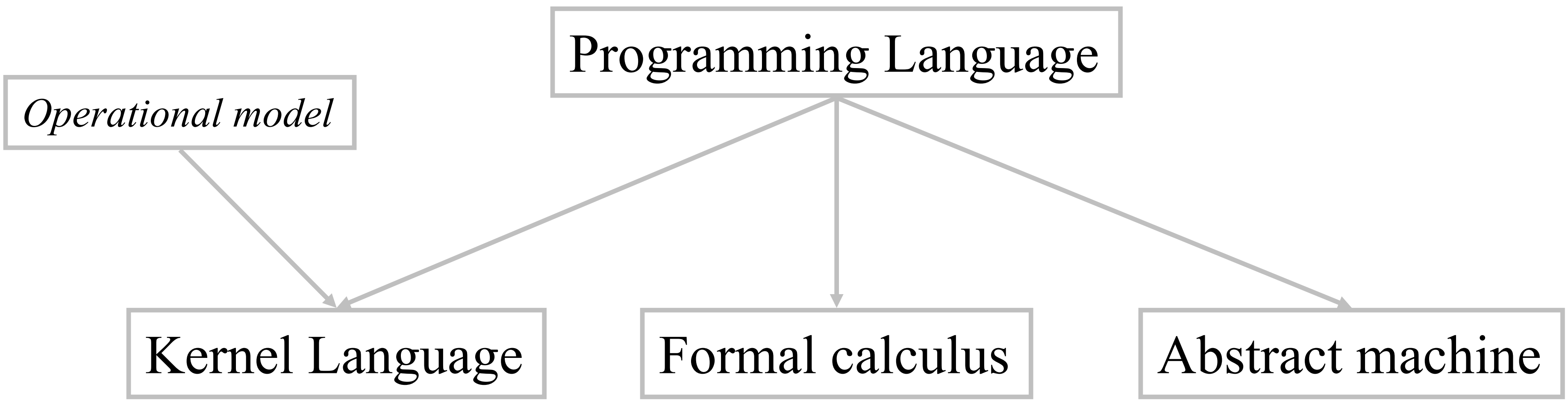
Linguistic abstractions vs. syntactic sugar

- 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
```

Approaches to semantics



Aid the programmer in reasoning and understanding

Mathematical study of programming (languages)
λ-calculus, predicate calculus, π-calculus

Aid to the implementer
Efficient execution on a real machine

Exercises

35. Write a valid EBNF grammar for lists of non-negative integers in Oz.
36. 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:

      ((λx.x λy.y) λz.z)
37. The grammar

    <exp> ::= <int> | <exp> <op> <exp>

    <op> ::= + | *

    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.