Model-Driven Engineering (MDE)
Lecture 1: Metamodels and Xtext

Regina Hebig, Thorsten Berger

Reuses some material from: Andrzej Wasowski, Model-Driven Development, ITU Copenhagen
Where I am from

Universität Potsdam

WASP 2017 - MDE, Regina Hebig, Thorsten Berger
Introduction MDE

- Models and DSLs
Introduction MDE

- Models and DSLs

```html
<!DOCTYPE html>
<html>
<!-- created 2010-01-01 -->
<head>
<title>sample</title>
</head>
<body>
<p>Voluptatem accusantium totam rem aperiam.</p>
</body>
</html>
```
### Introduction MDE

- **Models and DSLs**

---

**An Overview of Domain-Specific Languages in Robotics**

hosted by DSLRob, initiated and maintained by A. Nordmann, N. Hochgeschwender, D. Wigand, and S. Wrede, updated on August 9th 2016

This is an index of all publications in the Robotics DSL Zoo. For a more structured overview have a look at the different Subdomains.

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<td>Architectures and Programming</td>
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</table>

http://corlab.github.io/dslzoo/all.html
How to build a language?
Architecture of a Compiler

- **Syntax**
  - String of characters
  - Lexing (scanning)
  - String of tokens
  - Parsing
  - Abstract syntax tree (AST)
  - Name & type analysis

- **Semantics**
  - Annotated AST
  - Translation
  - Intermediate language
  - Register allocation
  - Assembly code
  - Assembler
  - Machine code

```
\text{\$t\', \text{x}', \', \'+', \text{\'3}', \text{\'n}'
\text{\$r_{123} \gets r_{12} + r_3
\text{\$jz L5
\text{\$jmp [r_{123}]
```

```
\text{\$AX \gets BX} \text{+ CX
\text{\$jz L5
\text{\$jmp [AX]
```

```
\text{\$f0 07 67 a4 5d cd}
```
Language = Syntax and … → Concrete and Abstract Syntax

Concrete Syntax
Representation of a model instance/program as
- Text, with whitespace, parentheses, curly braces, …
- Graphs in an editor

Abstract Syntax
Elements and their relations independent of the representation
Language = Syntax and Semantics

Concrete Syntax
- Representation of a model instance/program as Text, with whitespace, parentheses, curly braces, ...
- Graphs in an editor

Abstract Syntax
- Elements and their relations independent of the representation

Static Semantics
- Semantics evaluable without executing/interpreting the model (using constraints), e.g.
  - Compile-time correctness of a program: are variables declared? is it well-typed?

Dynamic Semantics
- The meaning or effect of a model/program at run-time; what happens when it is executed?; captured by generated code or interpreter
Architecture of a Compiler

Does it need to be so complex?
Building a Language with Model-Driven Techniques

Meta Model (abstract syntax) allows to create and edit instances

Editor (concrete syntax) triggers

relies on, consumes

Code Generator / Interpreter (semantics)
Abstract Syntax: Metamodeling
Before we Start: Reminder Class Modeling

- UML Class Diagram are used to meta-models (abstract syntax of a DSL)
- Allow structural and conceptual modeling

Definition: A class is an abstraction that specifies attributes of a set of concept instances (objects) and their relations to other concepts (classes).

<table>
<thead>
<tr>
<th>MyClass</th>
</tr>
</thead>
<tbody>
<tr>
<td>attributeInt: Integer</td>
</tr>
<tr>
<td>attributeDouble: Double</td>
</tr>
<tr>
<td>attributeOther: MyOtherClass</td>
</tr>
<tr>
<td>void operation1()</td>
</tr>
<tr>
<td>void operation2(int a)</td>
</tr>
</tbody>
</table>

Class Name: MyClass
Class Property: attributeInt, attributeDouble, attributeOther
Class Property of Other Type: MyOtherClass
Class Operations (not used for meta-modelling): operation1, operation2
Before we Start: Reminder Class Modeling
Creating Class (Ecore) Diagrams with EMF

- Good tutorial: https://www.eclipse.org/ecoretools/
Meta-Modeling

- Meta-modeling is *modeling modeling languages*
  - The Greek prefix "meta" means "about" - meta-model states something "about" other models
  - EMF is the most popular tool in this space
  - Tools can generate editors, serializers, and data structures from meta-models

- Why use meta-models in language definitions?
  - Concise and precise definition of the language concepts
  - Standardized exchange format
  - Checking correctness of models
  - Management of models in repositories
Meta-Model: Lego

Meta-Model
Building
Rules

Building Block

* connected with

Model
Lego

Real world
House

Images: pixelquelle.de
**Meta-Model: Languages**

**Meta-Model**
Building Rules

**Model**
A natural description

“A nice brown and white coloured house in the middle of the black forest”

**Real world**
House
A meta-model is a model that precisely defines the parts and rules needed to create valid models.

- **Parts**: domain concepts (model elements)

→ Metamodel defines the abstract syntax of a language
Elements and their relations independent of the representation
Abstract vs. Concrete Syntax (1)

Abstract Syntax

Music notation

Meta-Model

conforms to

Model

Music sheet

Concrete (Graphical) Syntax

Conforms to the Meta-Model
Abstract vs. Concrete Syntax (2)

Abstract Syntax

<table>
<thead>
<tr>
<th>Name: Attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>attributeName=&quot;Name&quot;</td>
</tr>
<tr>
<td>type=&quot;String&quot;</td>
</tr>
</tbody>
</table>

Lecturer: Class

<table>
<thead>
<tr>
<th>Lecturer: Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>className=&quot;Lecturer&quot;</td>
</tr>
</tbody>
</table>

Concrete Syntax

<table>
<thead>
<tr>
<th>Lecturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name: String</td>
</tr>
</tbody>
</table>

Class Lecturer {
    String Name;
}

<modelclass Lecturer {
    attributes
    ({
        Name : Type String
    })
}

Compare to the AST concept in compiler construction!
A mapping maps elements of the concrete syntax to the meta-model elements.

```xml
<class
className="Lecturer">
  <attribute
    attributeName="Name"
    type="String"/>
</class>
```

There is a standard that states the mapping from (MOF) models to XML: XMI (XML Metadata Interchange)
Abstract vs. Concrete Syntax (3)

- There can be many concrete syntaxes for an abstract syntax
- Different types
  - Textual
  - Graphical
  - ...
Have a look at the 2 metamodels in the handout. Both metamodels stem from students who participated in the Spring 2017 MDE course at Chalmers. The metamodels function as basis for two DSLs that allow the definition of custom made Lego bricks.

Discuss the models with your neighbors (2-3 persons) and try to answer the following questions:

1. Have a look at differences and commonalities between the 2 metamodels. Consider that the metamodels are the basis of two DSLs. Try to name
   • 2-3 features that you expect work in both DSLs.
   • At least 1 feature that you expect to work in only one of the DSLs

2. When having a look at the metamodels, can you identify a common design principle? (Hint: have a look at something that holds for most classes, direct or by inheritance)
Design Guidelines
Design Guidelines

- In EMF all objects (and thus all classes) must be directly or indirectly owned by a single root class
- Meta-models should have a single partonomy
Design Guidelines

- It is a bad smell if you see interfaces or methods in your meta-model.
- It is useful to verify the taxonomy (generalization hierarchy) of the meta-model with domain experts.
- If relations between concepts have properties, you can reify them as classes.
- It is a bad smell if multiple classes have the same property.
  - Recall the abstract class NamedElement.
Wrap-up Metamodels
Wrap-up Metamodels

- Class modeling
  - Classes represent domain concepts
  - Class modeling is a means for meta-modeling

- Meta-modeling
  - Meta-models model models, i.e., meta-models are languages in which models are expressed
  - Describe the abstract syntax; concrete syntaxes associated

- Meta-levels
  - Meta-Modeling languages, such as Ecore, can be used to model meta-models (i.e., languages)
  - Both use the concept of class modeling
Editors Generated from Metamodel
Wrap-up Metamodels

- Meta Model (abstract syntax)
- Model
- Editor (concrete syntax)
- Code Generator / Interpreter (semantics)

- allows to create and edit instances
- relies on, consumes
- triggers

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Concrete Syntax
Concrete Syntax

Meta Model (abstract syntax) allows to create and edit instances

Editor (concrete syntax)

relies on, consumes

triggers

Code Generator / Interpreter (semantics)

Model visualization

Model
FSM Example:

**Textual**

**STATES**
- State 1, State 2, Start(start), Stop 1(stop), Stop 2(stop)

**TRANSITIONS**
- Start->State 1, State 1 -b-> State 2, State 2 -e-> State 2,
- State 2 -c-> Stop 1, State 1 -a-> Stop 2

**Graphical**

![Finite State Machine Diagram]

- States: State 1, State 2
- Transitions: a -> State 1, b -> State 2, c -> Stop 1, e -> State 2
• Generative approaches available for …
  • graphical (e.g., Eclipse GMF)
  • and textual external DSLs (e.g., Xtext)
Basics: Grammar
Syntax Trees

- How are tokens organized into phrases?

Possible grammatical structure

```
expr  
expr  
expr  
  +  
  *  
  
```

How do we specify all legal syntax trees like this one?

Context-free grammar

```
expr →₁ expr + expr
expr →₂ expr * expr
expr →₃ ID
```

Derivation Tree

```
expr  
  1  
  3
expr  
  2
expr  
  3
```

The grammar is ambiguous!

rule 1
rule 2
rule 3
rule 3
rule 3
Context-Free Grammars

Context-Free Grammar
- Set of productions over disjoint sets of terminal symbols (tokens) and nonterminal symbols
- Production rewrites a nonterminal (left) to a list of terminals and nonterminals (right)
- Any nonterminal used on the right of a production appears on the left of some production
- One nonterminal is a start symbol

Context-Free Language
- Let $\alpha$, $\beta$ and $\gamma$ be sequences of symbols
- A derivation relation: $\alpha N \beta \Rightarrow \alpha \gamma \beta$ iff $N \rightarrow \gamma$
- A CFG $G$ over terminals $T$ defines a context-free language over $T \{ w \in T^* \mid S \Rightarrow^* w \}$. Each regular language is context-free
Extended Backus-Naur Form (EBNF): Syntactic Sugar

alternative: \[ S \rightarrow \alpha | \beta \rightarrow \begin{cases} S \rightarrow \alpha \\ S \rightarrow \beta \end{cases} \]

optional: \[ S \rightarrow \alpha \ T \ ? \ \beta \rightarrow \begin{cases} S \rightarrow \alpha \ T' \ \beta \\ T' \rightarrow T \ | \ \varepsilon \end{cases} \]

Kleene*: \[ S \rightarrow \alpha \ T \star \ \beta \rightarrow \begin{cases} S \rightarrow \alpha \ T' \ \beta \\ T' \rightarrow (T \ T') \ ? \end{cases} \]

grouping: \[ S \rightarrow \alpha (\beta) \ \gamma \rightarrow \begin{cases} S \rightarrow \alpha \ T' \ \gamma \\ T' \rightarrow \beta \end{cases} \]

Example

op → "+" | " * "
exp → exp op exp | ID | "(" exp ")"
The Chomsky Hierarchy

LL-Parsing

- Parser: component translating a sequence of tokens to a data structure representing a parse tree

Recall our example grammar

expr →₁ expr "+" expr
expr →₂ expr "*" expr
expr →₃ ID

Ambiguity (conflict)

Derive from a start symbol expr:

- x + y * z → use rule 1?
- x + y * z → or rule 2?

Not an ANTLR error!

LL(k) grammar

A for which always the next production in a left derivation can be selected deterministically (unambiguously) based on reading next k tokens.

LL(*) parser

Selects productions by recognizing if following tokens belong to regular language (no limit on prefix length).
LL-Parsing

Torben Ægidius Mogensen. Introduction to Compiler Design. Springer-Verlag London Limited. 2011 <- has a guide on writing and disambiguating grammars
XText

For External DSLs
Grammar is defined in an EBNF-like format in the xText editor.

The editor provides code completion and constraint checking for the grammars themselves.

Grammar is a collection of Rules. Each Rule is responsible for one metamodel element.
Example of a Generated Xtext-based Editor
How to start?

- No need to use EMF – Xtext allows starting with the grammar, and then generates a meta-model.
- If starting with EMF, Xtext generates a default textual syntax; you should adjust it later to your taste.
Xtext Walkthrough

- Make sure the Xtext Complete SDK is installed
- Create the `.ecore` file with the meta-model
- Create the default generator model for the meta-model
- Generate model code using the generator model
- Add the Xtext nature to the project with the meta-model (project context menu -> Configure -> Convert to Xtext project)
- Create an Xtext project from existing Ecore models, using the genmodel
- Generate Xtext code (in the grammar, context menu: Run As -> Generate Xtext Artifacts)
- Run your first DSL editing environment (Eclipse application)
- Iteratively revise the grammar to increase usability

more details:
https://eclipse.org/Xtext/documentation/301_grammarlanguage.html
http://www.eclipse.org/Xtext/documentation/1_0_1/xtext.pdf
xtext tutorial in 06 – concrete syntax.pdf
**Xtext Grammar Specifications (1)**

- **Declare** grammar name and **import** grammars that you **reuse**:
  ```plaintext
grammar mdsebook.Fsm with org.eclipse.xtext.common.Terminals
```

- **Import** meta-models (make types and methods available in the grammar):
  ```plaintext
2 import "http://www.mdsebook.org/mdsebook.fsm"
3 import "http://www.eclipse.org/emf/2002/Ecore" as.ecore
```

- The first symbol (left-hand side of first production rule) is the **start symbol**:
  ```plaintext
4 FiniteStateMachine returns FiniteStateMachine:
5  'FiniteStateMachine' name=EString
6  '{
7    'initial' initial=[State|EString]
8    'states' '{' states+=State (',' states+=State)* '}'
9  '}'
```
Xtext Grammar Specifications (2)

- **line 1:** `returns` introduces the type instantiated for a nonterminal
  - Terminals are ’quoted’ as strings

```
1 FiniteStateMachine returns FiniteStateMachine:
2   'FiniteStateMachine' name=EString
3     '{'
4     'initial' initial=[State|EString]
5     'states' '{' states+=State ( ',', states+=State)* '}'
6    '}
```

- **line 2:** `EString` is a symbol matches string literal or ID from the imported grammar `org.eclipse.xtext.common.Terminals`
- **line 2:** `attribute` `name` refers to an attribute of `FiniteStateMachine`, the type of the currently parsed nonterminal
- **line 2:** `name=EString` : result of parsing the symbol is be stored in the respective attribute of the constructed object
terminal ID:

(`^`)?>('a'..'z'|'A'..'Z' |_') ('a'..'z'|'A'..'Z'|'_'|'0'..'9')*;

- starts with an optional character (`^`)
- followed by a letter ('a'..'z'|'A'..'Z') or underscore `_`
- followed by any number of letters, underscores or/and numbers ('0'..'9')

**line 5:** EBNF notation (parentheses, Kleene*, +, ?, etc are available)

```plaintext
FiniteStateMachine returnsFiniteStateMachine:
1    'FiniteStateMachine' name=EString
2    '{
3        'initial' initial=[State|EString]
4        'states' '{' states+=State ( ',', states+=State)* '}'
5    '}
6    '}
```
Xtext Grammar Specifications (4)

- **line 5:** assignment "+=" extends a collection
- **References:**
  - **line 4:** a more complex name of parsing an attribute. Square brackets mean that the parsed `EString` is a reference to a `State` object
  - In general: `storingAttribute=[ReferredType|ReferenceSyntax]`
  - Object needs to have an attribute `name` for this to work automatically

```
FiniteStateMachine returns FiniteStateMachine:
'FiniteStateMachine' name=EString
'{
  'initial' initial=[State|EString]
  'states' '{' states+=State ( ',' states+=State)* '}'
'}';
```

- `ReferenceSyntax` defaults to `ID` if omitted
A Grammar for Finite State Machines

- The previous snippets were automatically generated by Xtext
- Let’s modify that a bit to obtain our preferred grammar:

```plaintext
// (c) mdsebook, wasowski, berger
grammar mdsebook.Fsm with org.eclipse.xtext.common.Terminals

import "http://www.mdsebook.org/mdsebook.fsm"
import "http://www.eclipse.org/emf/2002/Ecore" as.ecore

FiniteStateMachine:
  'machine' name=ID ['initial' initial=[State|ID]
  (states+=State)* ']';

State:
  'state' name=ID ['leavingTransitions+=Transition* ']';

Transition:
  'on' 'input' input=STRING ('output' output=STRING)?
  'and' 'go' 'to' target=[State];
```
Syntax for Finite State Machines

- And launch our generated editor
Left Recursion

Expression:

{IntConstant} value=INT | {StringConstant} value=STRING | {BoolConstant} value=('true'|'false') | {VariableRef} variable=[Variable] | {Plus} left=Expression '!' right=Expression;

2 errors, 13 warnings, 0 others

<table>
<thead>
<tr>
<th>Description</th>
<th>Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td>The rule 'Expression' is left recursive.</td>
<td>Expressions.xtext</td>
</tr>
<tr>
<td>This rule call is part of a left recursive call graph.</td>
<td>Expressions.xtext</td>
</tr>
</tbody>
</table>

[Be16]
**Left-Recursion**

- That grammar was not only ambiguous but also left-recursive.
- A **nonterminal X is left-recursive** if the left-most symbol in any of its productions is X itself, or rewrites to X again.
- A **grammar is left-recursive** if it has a left-recursive nonterminal.
- **LL parsers can’t** deal with left-recursive grammars (incl. ANTLR and hence Xtext).

```
expr → expr (‘+’ | ‘*’) expr
expr → INT | FLOAT | ID
expr → ‘(‘ expr ‘)’
```

expr is both left- and right-recursive above (but right-recursive is fine for LL-parsers)

```
term → factor ‘*’ factor
term → factor
factor → INT | FLOAT | ID
factor → ‘(‘ expr ‘)’
expr → term (‘+’ term)*
```
In the handout you find the Xtext grammar and an example instance for the first Lego DSL (see Metamodels from the earlier handout).

Together with your neighbor:

1. Try to map metamodel classes and associations to elements in the grammar. Which elements do you find reflected and how? How are associations and containment relationship represented?

2. Have a look at the instance below. Make a guess what it could describe.

https://eclipse.org/Xtext/documentation/301_grammarlanguage.html
Xtext (15 minutes)
Wrap-up Syntax & Outlook Semantics

- Semantics

- How to prepare:
  - Download the assignment and code already – we will have a look at the assignment and you can ask questions
Model-Driven Engineering (MDE)

Regina Hebig, Thorsten Berger
Literature - Metamodeling

- Book
  - 03 - meta-modeling.pdf
  - appendix b - class modeling.pdf
  - appendix c - using eclipse emf.pdf
Literature

- Book
  - Chapter 6 (Concrete Syntax)
    - contains an appendix with an Xtext tutorial

- Xtext
    - freely available ebook
    - very hands-on description of Xtext
  - Xtext documentation and guide
    - https://www.eclipse.org/Xtext/documentation/2.5.0/Xtext%20Documentation.pdf