Metamodeling and Metaprogramming

Slides by courtesy of U. Assmann, IDA / TU Dresden, 2004
Revised 2005, 2006 by C. Kessler, IDA, Linköpings universitet

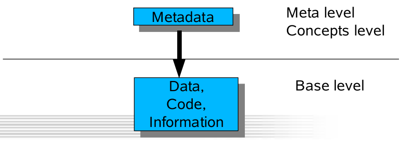
U. Assmann: *Invasive Software Composition*, Sect. 2.2.5 Metamodeling;
C. Szyperski: *Component Software*, Sect. 10.7, 14.4.1 Java Reflection

1. Introduction to Metalevels

"A system is about its domain.
A reflective system is about itself"
Patti Maes, ACM OOPSLA 1987

Metadata

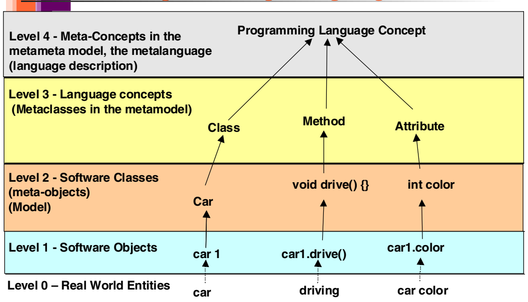
- *Meta*: means "describing"
- *Metadata*: describing data (sometimes: self-describing data). The type system of metadata is called *metamodel*
- *Metalevel*: the elements of the meta-level (the *meta-objects*) describe the objects on the *base level*
- *Metamodeling*: description of the model elements/concepts in the metamodel



Example: Different Types of Program Semantics and their Metalanguages (Description Languages)

- **Syntactic structure**
  - Described by a *context free grammar*
  - Does not consider context
- **Static Semantics**
  - Described by *context sensitive grammar* *(or attribute grammar, denotational semantics, logic constraints)*
  - Describes context constraints, context conditions
  - Can describe consistency conditions on the specifications
    - "If I use a variable here, it must be defined elsewhere"
    - "If I use a component here, it must be alive"
- **Dynamic Semantics**
  - Interpreter in an *interpreter language (e.g., lambda calculus)*
  - Sets of runtime states or terms

Metalevels in Programming Languages



Classes and Metaclasses

Classes in a software system

```
class WorkPiece { Object belongsTo; }
class RotaryTable { WorkPiece place1, place2; }
class Robot { WorkPiece piece1, piece2; }
class Press { WorkPiece place; }
class ConveyorBelt { WorkPiece pieces[]; }
```

Concepts of a metalevel can be represented at the base level.
This is called ***reification***.

Metaclasses

```
public class Class {
  Attribute[] fields;
  Method[] methods;
  Class ( Attribute[] f, Method[] m) {
    fields = f;
    methods = m;
  }
}
public class Attribute {..}
public class Method {..}
```

Examples:
- Java Reflection API [Szyperski 14.4.1]
- UML metamodel (MOF)

Creating a Class from a Metaclass

```
class WorkPiece { Object belongsTo; }
class RotaryTable { WorkPiece place1, place2; }
class Robot { WorkPiece piece1, piece2; }
class Press { WorkPiece place; }
class ConveyorBelt { WorkPiece pieces[]; }
```

```
public class Class {
  Attribute[] fields;
  Method[] methods;
  Class ( Attribute[] f, Method[] m) {
    fields = f;
    methods = m;
  }
}
public class Attribute {..}
public class Method {..}
```

- Example: Create a class by instantiating the metaclass:

```
Class WorkPiece = new Class( new Attribute[]{ "Object belongsTo" }, new Method[]{});
Class RotaryTable = new Class( new Attribute[]{ "WorkPiece place1", "WorkPiece place2" },
                               new Method[]{});
Class Robot    = new Class( new Attribute[]{ "WorkPiece piece1", "WorkPiece piece2" },
                            new Method[]{});
Class Press    = new Class( new Attribute[]{ "WorkPiece place" }, new Method[]{});
Class ConveyorBelt = new Class( new Attribute[]{ "WorkPiece[] pieces" }, new Method[]{});
```

Metaprogram at base level

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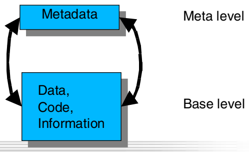
Reflection (Self-Modification, Metaprogramming)

- **Reflection** is computation about the metamodel in the base model.
- The application can look at its own skeleton (metadata) and may even change it
  - Allocating new classes, methods, fields
  - Removing classes, methods, fields

Remark: In the literature, "reflection" was originally introduced to denote "computation about the *own* program" [Maes'87] but has also been used in the sense of "computing about *other* programs" (e.g., components).



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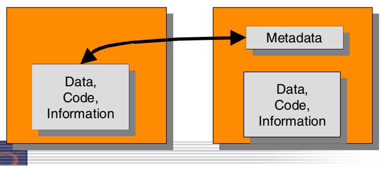
Introspection

- Read-only reflection is called ***introspection***
  - The component can look up the metadata of itself or another component and learn from it (but not change it!)
- Typical application: find out features of components
  - Classes, methods, attributes, types
  - Very important in component supermarkets



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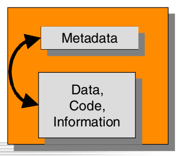
Introcession

- Read and Write reflection is called ***introcession***
  - The component can look up the metadata of itself or another component and may change it
- Typical application: dynamic adaptation of parts of own program
  - Classes, methods, attributes, types



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Reflection Example

Reading Reflection (Introspection):

```
for all c in self.classes do
  generate_class_start(c);
  for all a in c.attributes do
    generate_attribute(a);
  done;
  generate_class_end(c);
done;
```

Full Reflection (Introcession):

```
for all c in self.classes do
  helpClass = makeClass(c.name+"help");
  for all a in c.attributes do
    helpClass.addAttribute(copyAttribute(a));
  done;
  self.addClass(helpClass);
done;
```

A ***reflective system*** is a system that uses this information about itself in its normal course of execution.

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Metaprogramming on the Language Level

```
enum { Singleton, Parameterizable } BaseFeature;
public class LanguageConcept {
  String name;
  BaseFeature singularity;
  LanguageConcept ( String n, BaseFeature s ) {
    name = n;
    singularity = s;
  }
}
```

Metalanguage concepts
Language description concepts
(Metametamodel)

Language concepts
(Metamodel)

```
LanguageConcept Class = new LanguageConcept("Class", Singleton);
LanguageConcept Attribute =
                    new LanguageConcept("Attribute", Singleton);
LanguageConcept Method =
                new LanguageConcept("Method", Parameterizable);
```

Made It Simple

- Level 1: objects
- Level 2: classes, types
- Level 3: language elements
- Level 4: metalanguage, language description language

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Use of Metamodels and Metaprogramming

- To model, describe, introspect, and manipulate
- Workflow systems, such as ARIS [Scheer'98]
- Databases
- Debuggers
- Programming languages, such as Java Reflection API
- Component systems, such as JavaBeans or CORBA DII
- Composition systems, such as Invasive Software Composition
- Modeling systems, such as UML or Modelica
- ... probably all systems ...

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2. Metalevel Architectures

- Reflective architecture
- Metalevel architecture

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Reflective Architecture

- A system with a ***reflective architecture*** maintains *metadata* and a *causal connection* between meta- and base level.
  - The metaobjects describe structure, features, semantics of domain objects
  - This connection is kept consistent
- *Reflection* is thinking about oneself (or others) at the base level with the help of metadata
- *Metaprogramming* is programming with metaobjects, either at base level or meta level

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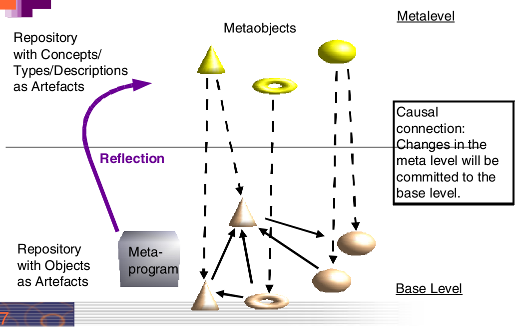
Reflective Architecture



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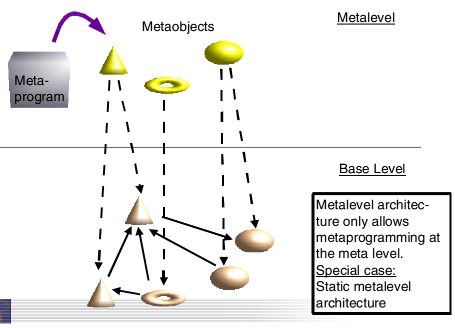
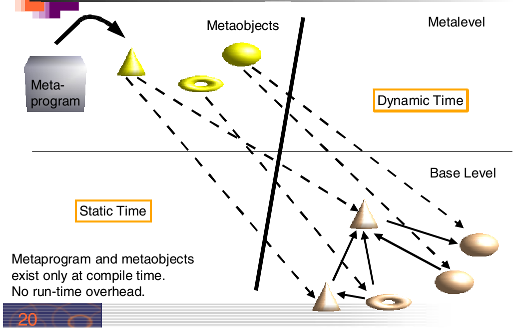
Metalevel Architecture

- In a *metalevel architecture*, the metamodel is used for computations,
  - but the metaprograms execute *either* on the metalevel *or* on the base level.
- Special variants:
  - *Introspective architecture* (no self-modification)
    - Example: Java Reflection API
  - *Staged metalevel architecture* (metaprogram evaluation time is at system build time, different from system runtime)
    - Example: C++ templates (generics), expanded at compile time
    - Example: COMPOST composition programs configure programs

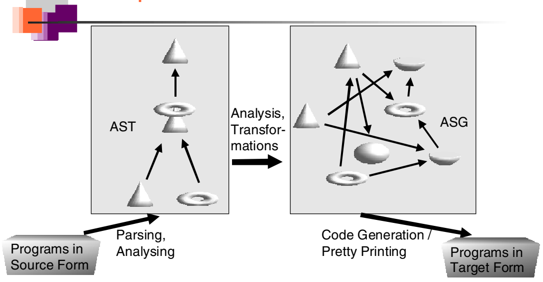
Metalevel Architecture



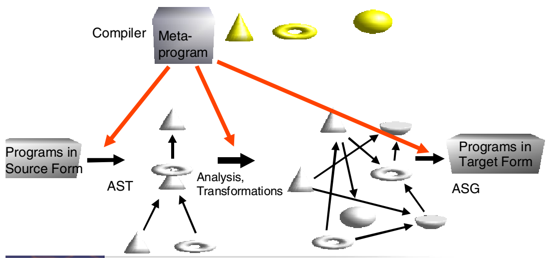
Static Metaprogramming Architecture



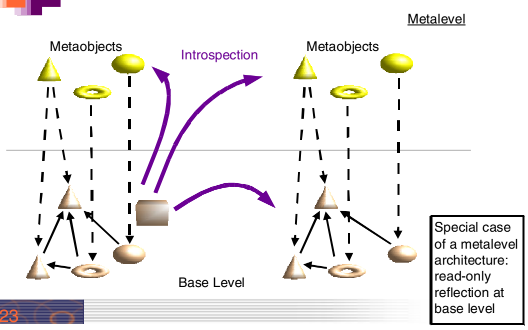
Compilers



Compilers Are Static Metaprograms



Introspective Architectures



3. Metaobject Protocols (MOP)

From structural to behavioral reflection

Metaobject Protocol

- A *metaobject protocol (MOP)* is an implementation of the methods of the metaclasses.
- It specifies an *interpreter* for the language,
  - describing the semantics, i.e., the behavior of the language objects
  - in terms of the language itself.
- By changing the MOP, the language semantics is changed
  - or adapted to a context.
- If the language is object-oriented, default implementations of metaclass methods can be overwritten by subclassing
  - thereby changing the semantics of the language

A Very Simple MOP

[ISC] p.52

```
public class Class {
  Class(Attribute[] f, Method[] m)
  {
    fields = f;  methods = m;
  }
  Attribute[] fields;
  Method[] methods;
}
```

```
public class Attribute {
  public String name;
  public Object value;
  Attribute (String n) { name = n; }
  public void enterAttribute() { }
  public void leaveAttribute() { }
  public void setAttribute(Object v) {
     enterAttribute();
     this.value = v;
     leaveAttribute();
  }
  public Object getAttribute() {
     Object returnValue;
     enterAttribute();
     returnValue = value;
     leaveAttribute();
     return returnValue;
  }
}
```

```
public class Method {
  public String name;
  public Statement[] statements;
  public Method(String n) { name = n; }
  public void enterMethod() { }
  public void leaveMethod() { }
  public Object execute {
    Object returnValue;
    enterMethod();
    for (int i = 0;
         i <= statements.length; i++) {
      statements[i].execute();
    }
    leaveMethod();
    return returnValue;
  }
}
public class Statement {
  public void execute() { ... }
}
```


An Adapted MOP

Adaptation by subclassing the metaclass Attribute

Meta level:

```
public class TracingAttribute extends Attribute {
  public void enterAttribute() {   // overload Attribute.enterAttribute()
    System.out.println("Here I am, accessing attribute " + name);
  }
  public void leaveAttribute() {
    System.out.println("I am leaving attribute " + name +
                       ": value is " + value);
  }
}
```

Base level:

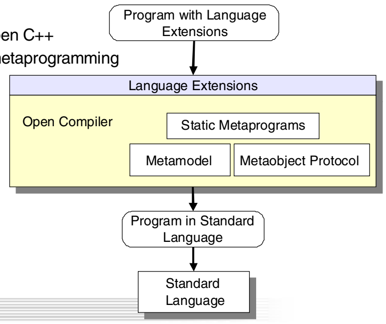
```
Class Robot = new Class( new Attribute[]{ "WorkPiece piece1",  "WorkPiece piece2" },
                         new Method[]{ "takeUp() { WorkPiece a = rotaryTable.place1; } "});

Class RotaryTable =  new Class( new TracingAttribute[]{ "WorkPiece place1",
                                                        "WorkPiece place2" },
                                new Method[]{});
```

```
Here I am, accessing attribute place1
I am leaving attribute place1: value is WorkPiece #5
```


Open Languages

- Open Java, Open C++
- Employ static metaprogramming



An Open Language

- ... offers its own metamodel for static metaprogramming
  - Its schema (e.g., structure of AST) is made accessible as an abstract data type
  - Users can write static metaprograms to adapt the language
  - Users can override default methods in the metamodel, changing the static language semantics or the behavior of the compiler
- ... can be used to adapt components at compile time
  - During system generation
  - Static adaptation of components
- Metaprograms are removed during system generation, no runtime overhead
  - Avoids the overhead of dynamic metaprogramming

4. Metaobject Facilities (MOF)

Example: Generating IDL specifications

IDL = Interface Description Language

- The type system of CORBA
- Maps to many programming language type systems
  - Java, C++, C#, etc.
- Is a kind of "mediating type system", least common denominator...
- For interoperability to components written in other languages, an interface description in IDL is required
- (See also lecture on CORBA)

Example: Generating IDL specs (cont.)

- Problem: How to generate an IDL spec from a Java application ?
- You would like to say (here comes the introspection:)

```
for all c in classes do
   generate_class_start(c);
   for all a in c.attributes do
      generate_attribute(a);
   done;
   generate_class_end(c);
done;
```

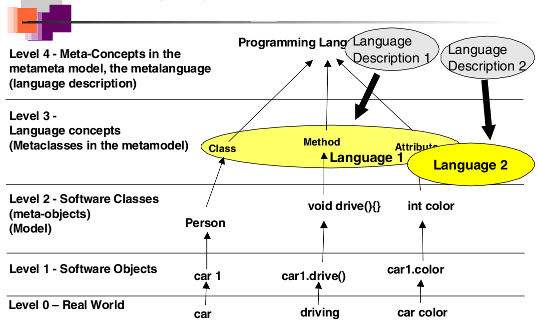
- Need a type system that describes the Java type system
  - With classes and attributes, methods
- Some other problems:
  - How to generate code for exchange between C++ and Java?
  - How to bind other type systems than IDL into Corba (UML, ..)?

Metaobject Facility (MOF)

- Metadata can be used to
  - Get knowledge about unknown data formats, types
  - Navigate in unknown data
  - Generate unknown data
    - Generate type systems (e.g., IDL from programming languages)
    - Generate languages from metalanguage specifications

A ***metaobject facility (MOF)*** is a generative mapping (transformer, generator) from the metalanguage level (Level 4) to the language level (Level 3)

The MOF Generator



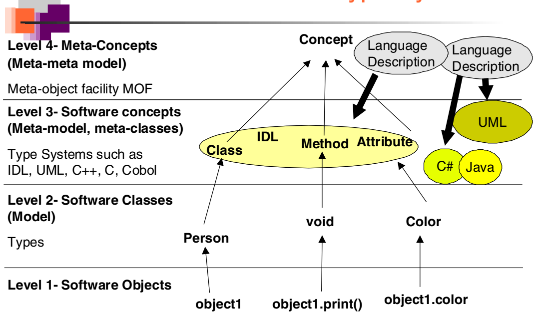
MOF: Example

- The MOF for the CORBA meta-metamodel contains a *type system for type systems*:
  - Entities
  - Relationships
  - Packages
  - Exceptions
- Can describe every type system of a programming or modeling language
- MOF concepts must be mapped to types of a specific type system
- From these mappings, code can be generated that provides services for that type system, e.g. code that navigates in object graphs.

Metaobject Facility (MOF)

- From different language descriptions, different (parts of) languages are generated
  - Type systems
  - Modelling languages (such as UML)
  - Component models
  - Workflow languages
- A MOF cannot generate a full-fledged language
- A MOF is not a MOP
  - The MOF is generative
  - The MOP is interpretative

Meta Levels in Corba Type Systems



Meta-meta-models describe general type systems!

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Metaobject Facility MOF in CORBA

- The OMG-MOF (metaobject facility) is a MOF, i.e., a metalanguage, describing type systems
  - Describing IDL, the CORBA type system
  - Describing the UML metamodel
  - Describing XML schema
  - Standardized Nov. 1997
- It is not a full metalanguage, but only contains
  - Classes, relations, attributes
  - OCL specifications to express constraints on the classes and their relations
  - A MOP cannot be specified in the MOF (methods are lacking in the MOF)

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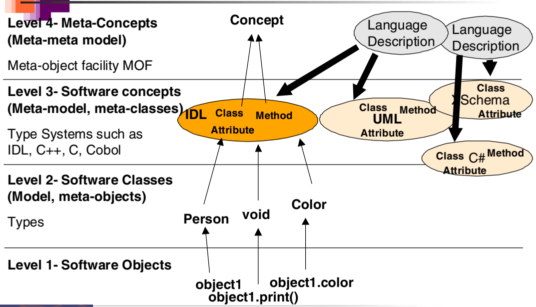
Meta Levels in Corba Type Systems



Meta-meta-models describe general type systems!

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Automatic Data Transformation with the Metaobject Facility (MOF)

- Given:
  - 2 different language descriptions
  - An isomorphic mapping between them
- Produced:
  - A transformer that transforms data in the languages
- Data fitting to MOF-described type systems can automatically be transformed into each other
  - The mapping is only an isomorphic function in the metametamodel
  - Exchange data between tools possible

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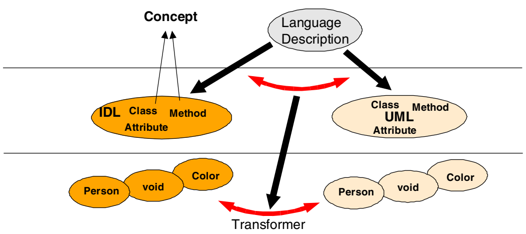
Isomorphic Language Mappings



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Reason: Similarities of Type Systems

- Metalevel hierarchies are similar for programming, specification, and modeling level
- Since the MOF can be used to describe type systems there is hope to describe them all in a similar way
- These descriptions can be used to generate
  - Conversions
  - Mappings (transformations) of interfaces and data

Summary MOF

- The MOF describes general type systems
- New type systems can be added, composed and extended from old ones
- Relations between type systems are supported
- For interoperability between type systems and -repositories
- Automatic generation of IDL
- Language extensions, e.g. for extending UML
- Reflection/introspection supported
- Application to workflows, data bases, groupware, business processes, data warehouses (Common Warehouse Model, CWM)

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5. Component Markup

.. A simple aid for introspection and reflection...

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Markup Languages

- Convey more semantics for the artifact they markup
- HTML, XML, SGML are markup languages
- Remember: a component is a container
- A markup can offer contents of the component for the external world, *i.e.*, for composition
  - It can offer the content for introspection
  - Or even intercession

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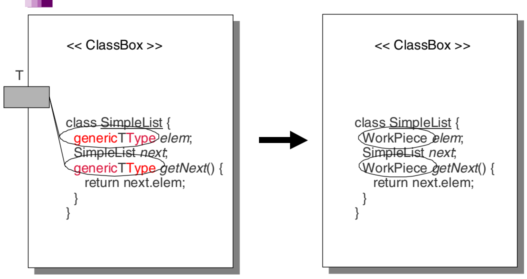
Hungarian Notation

- ***Hungarian notation*** is a markup method that defines naming conventions for identifiers in languages
  - to convey more semantics for composition in a component system
  - but still, to be compatible with the syntax of the component language
  - so that standard tools can still be used
- The composition environment can ask about the names in the interfaces of a component (introspection)
  - and can deduce more semantics

Generic Types in COMPOST



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Java Beans Naming Schemes

- Property access
  - setField(Object value);
  - Object getField();
- Event firing
  - fire<Event>
  - register<Event>Listener
  - unregister<Event>Listener

Metainformation for JavaBeans is identified by markup in the form of Hungarian Notation.
This metainformation is needed, e.g., by the JavaBeans Assembly tools to find out which classes are beans and what properties and events they have.

Markup by Comments

- Javadoc tags
  - @author
  - @date
  - @obsolete
- Java 1.5 attributes
- C# attributes
  - //@author
  - //@date
  - //selfDefinedData
- C# /.NET attributes
  - [author(Uwe Assmann)]
  - [date Feb 24]
  - [selfDefinedData(...)]

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Markup is Essential for Component Composition

- because it identifies metadata, which in turn supports introspection and introcession
- Components that are not marked-up cannot be composed
- Every component model has to introduce a strategy for component markup
- Insight: A component system that supports composition techniques must be a reflective architecture!

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What Have We Learned? (1)

- *Reflection* is reasoning and modification of oneself or others with the help of metadata.
  - Reflection is enabled by *reification* of the metamodel.
  - *Introspection* is thinking about oneself, but not modifying.
- *Metaprogramming* is programming with meta-objects.
- System has *reflective architecture* if metaprogram executes at base level and the base-model and metamodel are kept consistent
- System has *metalevel architecture* if it only supports metaprogramming at meta-level (not at the base level)
- A *MOP* can describe an interpreter for a language; the language is modified if the MOP is changed
- A *MOF* is a generator for (part of) a language
  - The CORBA MOF is a MOF for type systems mainly

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What Have We Learned? (2)

- Metamodeling, e.g. MOF for UML / Corba IDL / ...
- Some well-known examples of metaprogramming:
  - Static metaprogramming at base level e.g. C++ templates, AOP
  - Static metaprogramming at meta level e.g. Compiler analysis / transformations
  - Dynamic metaprogramming at base level e.g. Java Reflection
- Component and composition systems are **reflective architectures**
  - Markup marks the variation and extension points of components
  - Composition introspects the markup
  - Look up type information, interface information, property information or full reflection