11. Metadata, Metamodelling, and Metaprogramming

1. Searching and finding components
2. Metalevels and the metapyramid
3. Metalevel architectures
4. Metaobject protocols (MOP)
5. Metaobject facilities (MOF)
6. Metadata as component markup

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11.1. Searching and Finding Components in Repositories

It should be as easy to find good quality reusable software assets as it is to find a book on the internet

http://softwarereuse.nasa.gov/

Component Repositories

- Components must be stored in component repositories with **metadata (markup, attributes)** to find them again
- Descriptions (Metadata)
  - Attributes: Keywords, Author data
  - Usage protocols (behavioral specifications)
    - State machines
    - Sequence diagrams
    - Contracts (pre/post/invariants)
- Examples of Component Repositories
  - CORBA
    - implementation registry
    - interface registry
  - COM+ registry
  - Commercial Component Stores www.componentsource.com
  - Debian Linux Component System (apt, dpkg)
  - CTAN TeX Archive

Why Searching Components?

- A public component repository is called a **market**, managed by a **trader (broker)**
  - Distributing or selling components
  - Companies can register components at the the trader
  - Customers can search components in the markets and buy or rent them
- Searching for functionality (interface, contract, protocol)
  - Reuse instead of build
  - Searching for components to replace own ones
  - Semantic substituability (CM-S) should be ensured
- Searching for quality features
  - Performance, energy consumption, reliability

11.2. An Introduction to Metalevels

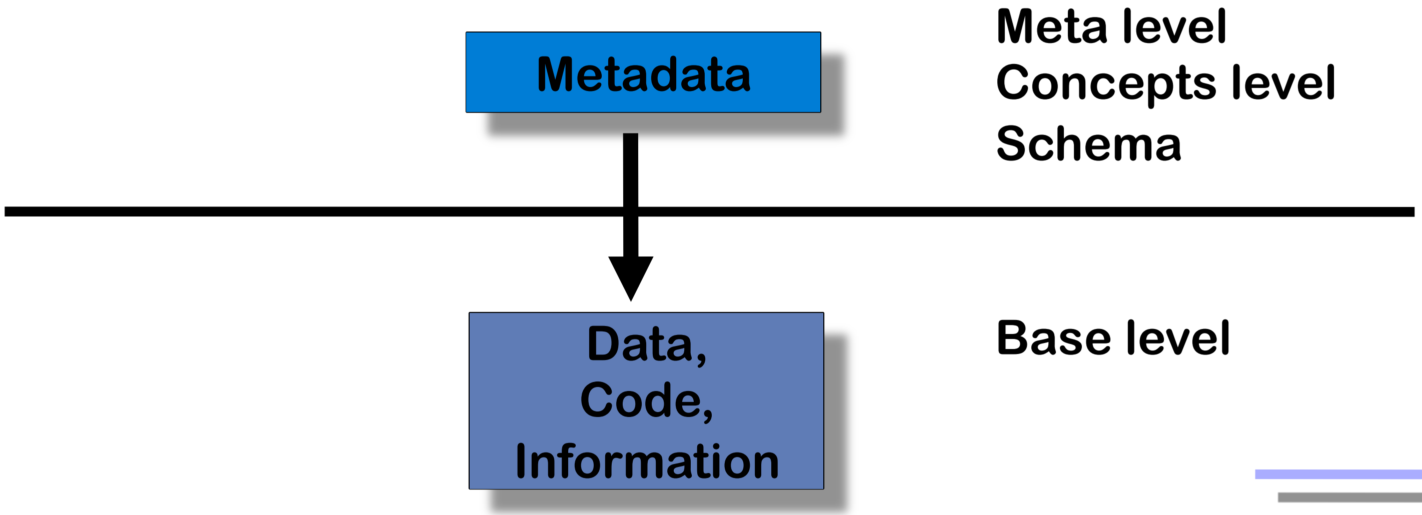
"A system is about its domain.

A reflective system is about itself"

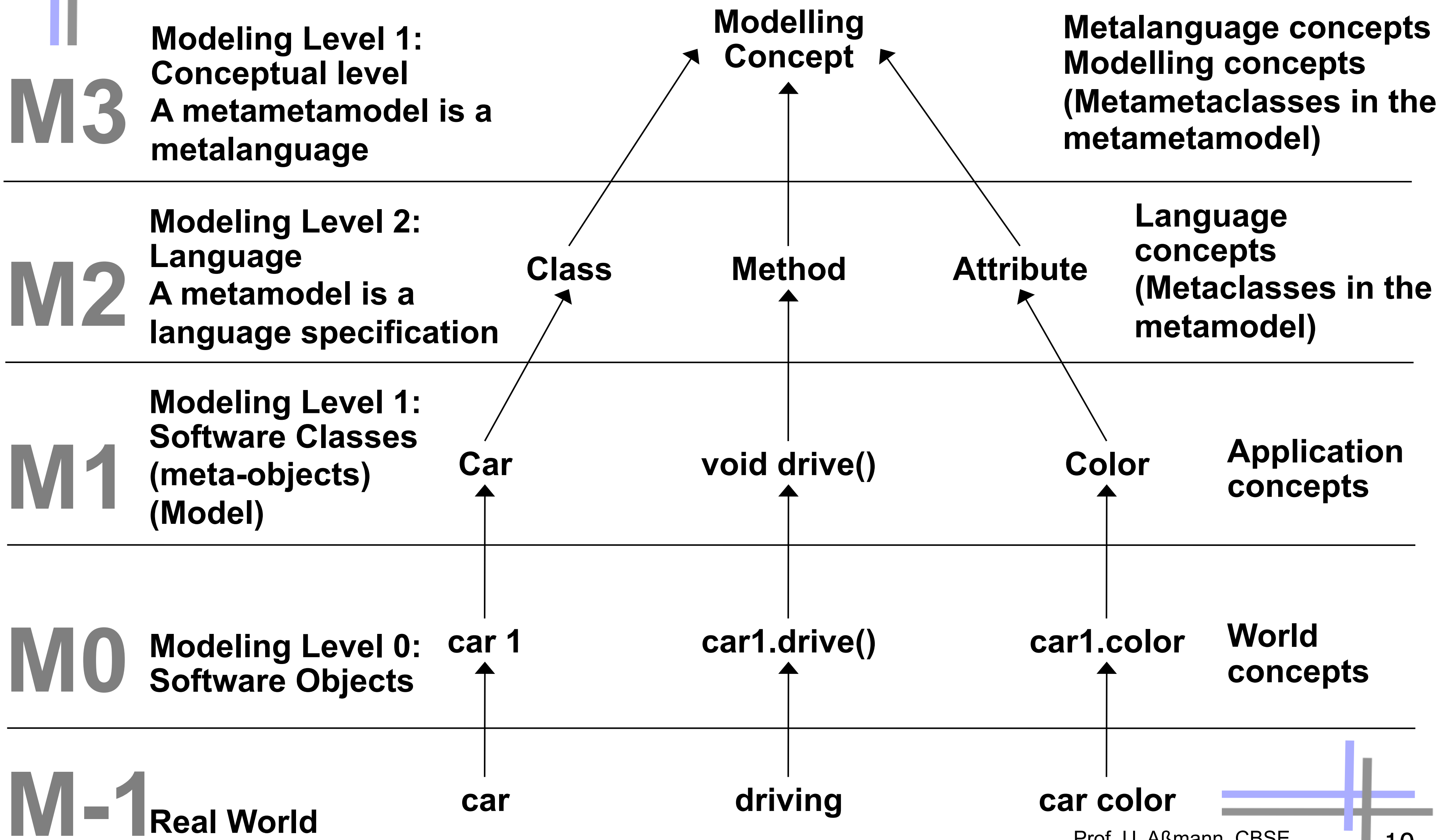
Maes, 1988

Metadata

- **Meta**: greek for “describing”
- **Metadata**: describing data (sometimes: self describing data). The type system 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
- **Metalanguage**: a description language for languages



Metalevels in Programming Languages (The Meta-Pyramid)



Different Types of Semantics and their Metalanguages (Description Languages)

Structure (context-free)

- Described by a *context-free grammar* or a *metamodel*
- Does not regard context

Static Semantics (context conditions on structure), **Wellformedness**

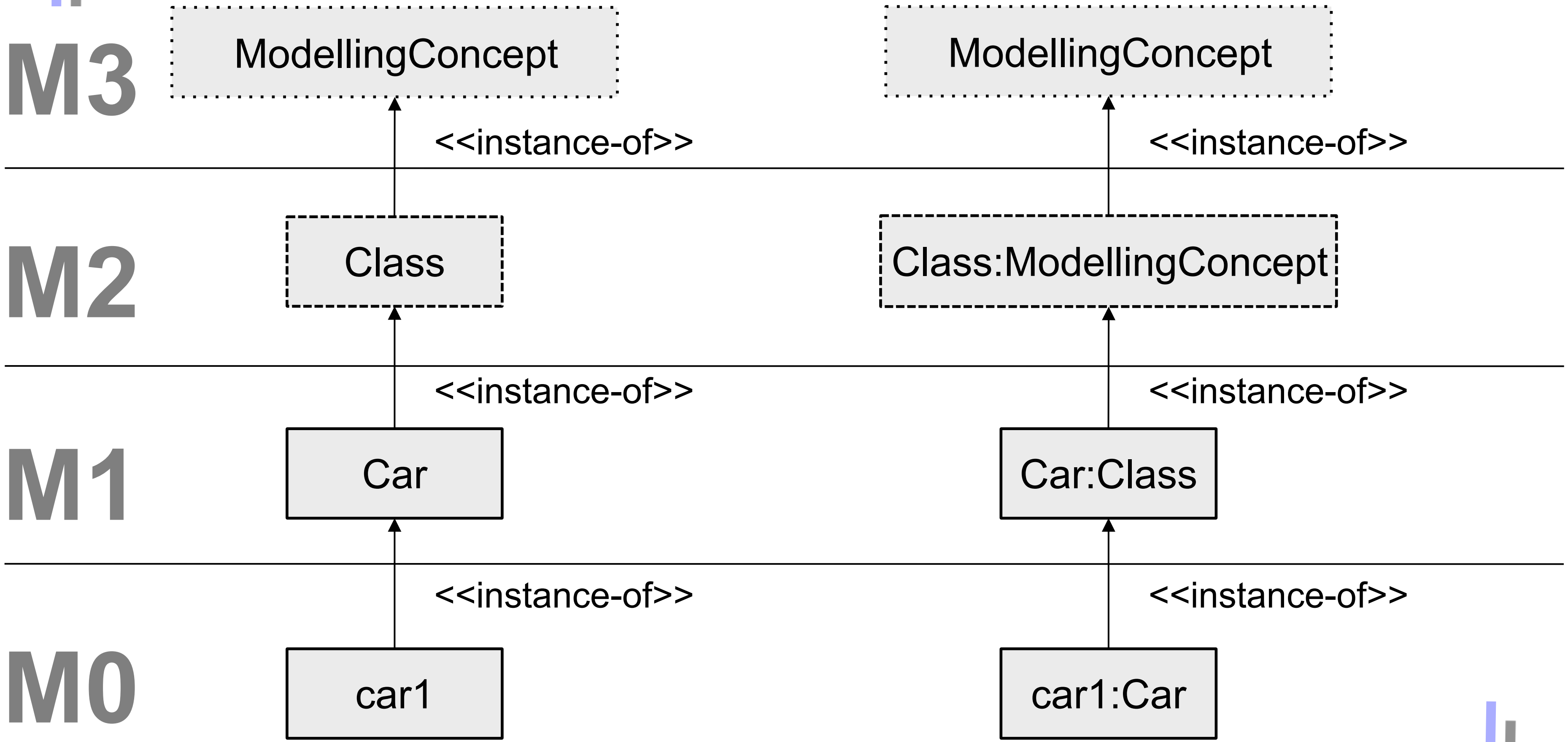
- Described by *context-sensitive grammar (attribute grammar, denotational semantics, logic constraints),* or a *metamodel with context constraints*
- Describes context constraints, context conditions, meaning of names
- Can describe consistency conditions on the specifications
  - “If I use a variable here, it must be defined elsewhere”
  - “If I use a component here, it must be alive”

Dynamic Semantics (Behavior)

- Interpreter in an *interpreter language (e.g., lambda calculus),* or a *metaobject protocol*
- A dynamic semantics consists of sets of run-time states or run-time terms
- In an object-oriented language, the dynamic semantics can be specified in the language itself. Then it is called a *meta-object protocol (MOP).*

Notation

- We write metaclasses with dashed lines, metametaclasses with dotted lines



Classes and Metaclasses

- Metaclasses are *schemata* for classes, i.e., describe what is in a class

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[]; }
```

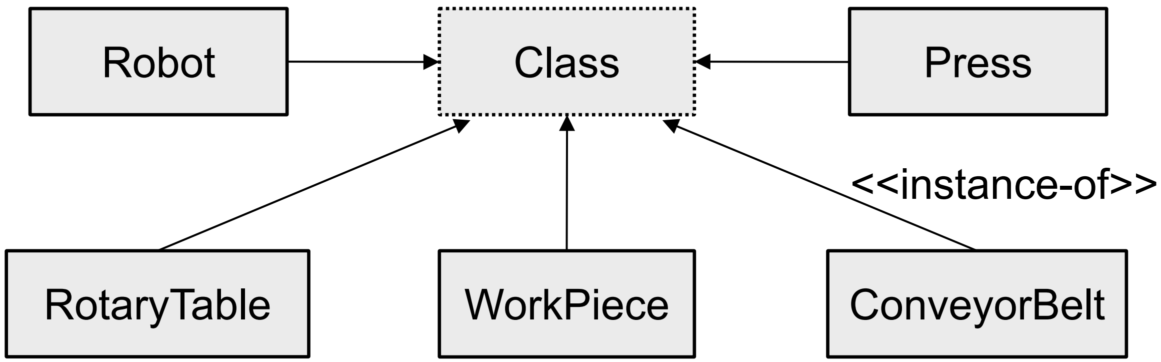
Metaclasses

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

public class Attribute {
   Object type;
   Object value; }

public class Method {
   String name; List parameters, MethodBody body; }

public class MethodBody { ... }
```

Creating a Class from a Metaclass

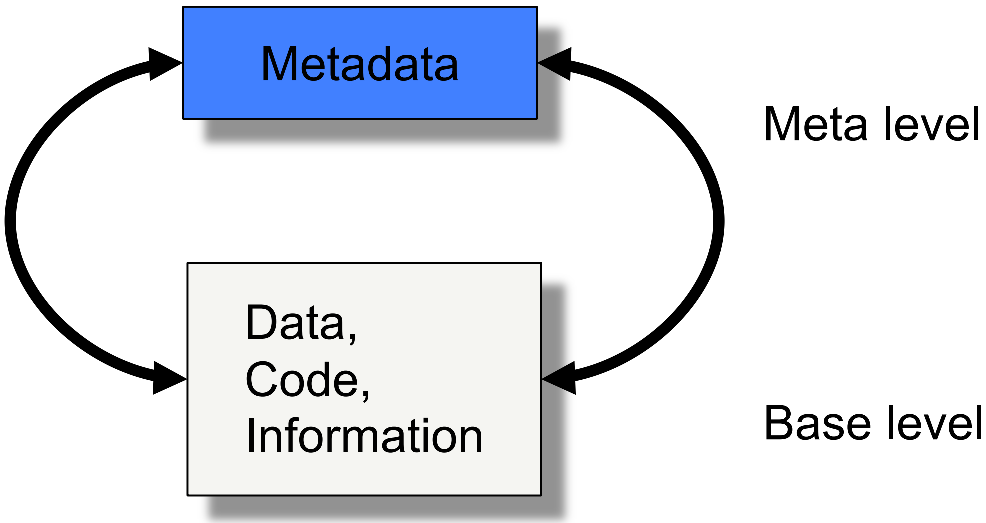
- Using the constructor of the metaclass (Pseudojava used here)
- Then, classes are special objects, instances of metaclasses

```
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[]{});
```



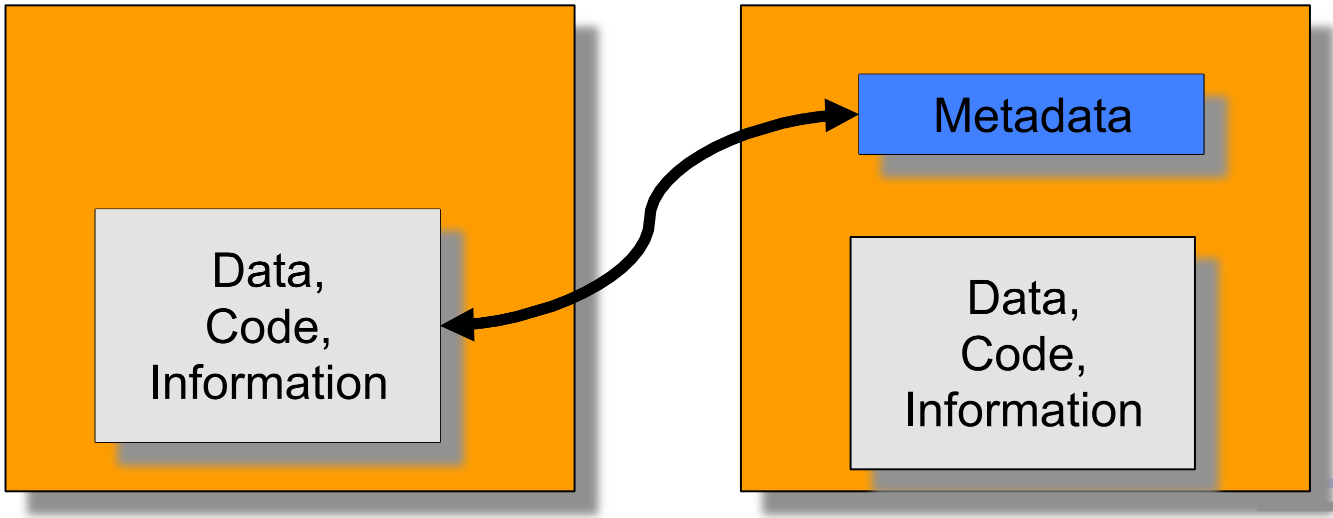
Reflection (Self-Modification, Intercession, Metaprogramming)

- Computation about the metamodel in the model is *reflection*
  - Reflection: thinking about oneself with the help of metadata
  - The application can look at their own skeleton and change it
    - Allocating new classes, methods, fields
    - Removing classes, methods, fields
- This self modification is also called *intercession* in a meta-object protocol (MOP)



Introspection

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



Reading Reflection (Introspection)

Used for generating something based on metadata information

```
Component component = .. Get from supermarket ..
for all cl in component.classes do
    generate_for_class_start(cl);

    for all a in cl.attributes do
        generate_for_attribute(a);
    done;

    for all m in cl.methods do
        generate_for_method(m);
    done;

    generate_for_class_end(cl);
done;
```

Full Reflection (Run-Time Code Generation)

Generating code, interpreting, or loading it

```
for all c in self.classes do
    helperClass = makeClass(c.name+"Helper");

    for all a in c.attributes do
       helperClass.addAttribute(copyAttribute(a));
    done;

    self.loadClass(helperClass);
    self.addClass(helperClass);
done;
```

A reflective system is a system in which the application domain is *causally connected* with its own domain.
Patti Maes

Reflective Class Replacement (Run-Time Updating)

Generating code, interpreting, or loading it

```
for all c in self.classes do
    helperClass = makeClass(c.name);
    for all a in c.attributes do
       helperClass.addAttribute(copyAttribute(a));
    done;

    self.deleteClass(c.name);
    self.loadClass(helperClass);
    self.addClass(helperClass);

-- migrate the state of the old objects to the new class
-- (migration protocol)
done;
```

Ericsson telephone base stations have a guaranteed down-time of some seconds a year.
Every second more costs at least 1 Mio Dollar.
Ericsson does extensive run-time updating

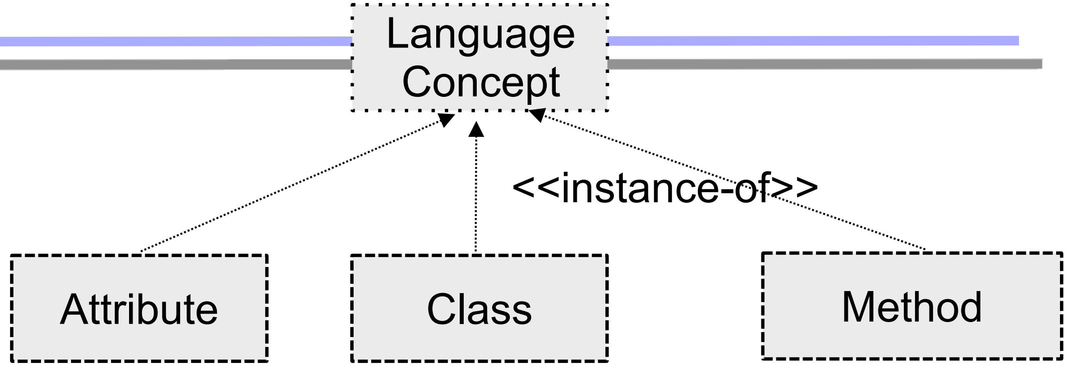
Reflective Class Replacement Versioning (Run-Time Updating)

Generating code, interpreting, or loading it

```
for all c in self.classes do
    helperClass = makeClass(c.name+"_version_"+c.VersionCounter);

    for all a in c.attributes do
       helperClass.addAttribute(copyAttribute(a));
    done;

    self.loadClass(helperClass);
    self.addClass(helperClass);
    c.objects (c.name,setDeprecated());
-- slowly let die out objects of old class
-- only allocate objects for new class
done;
```

Ericsson says: "We are not allowed to stop. We can kill, after some time, old calls. But during update, we have to run two versions of a class at the same time."

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

- Modeling Level M-1: real-world objects

- Modeling Level M0: objects in the running program
- Modeling Level M1: programs, classes, types
- Modeling Level M2: language
- Modeling Level M3: metalanguage, language description language

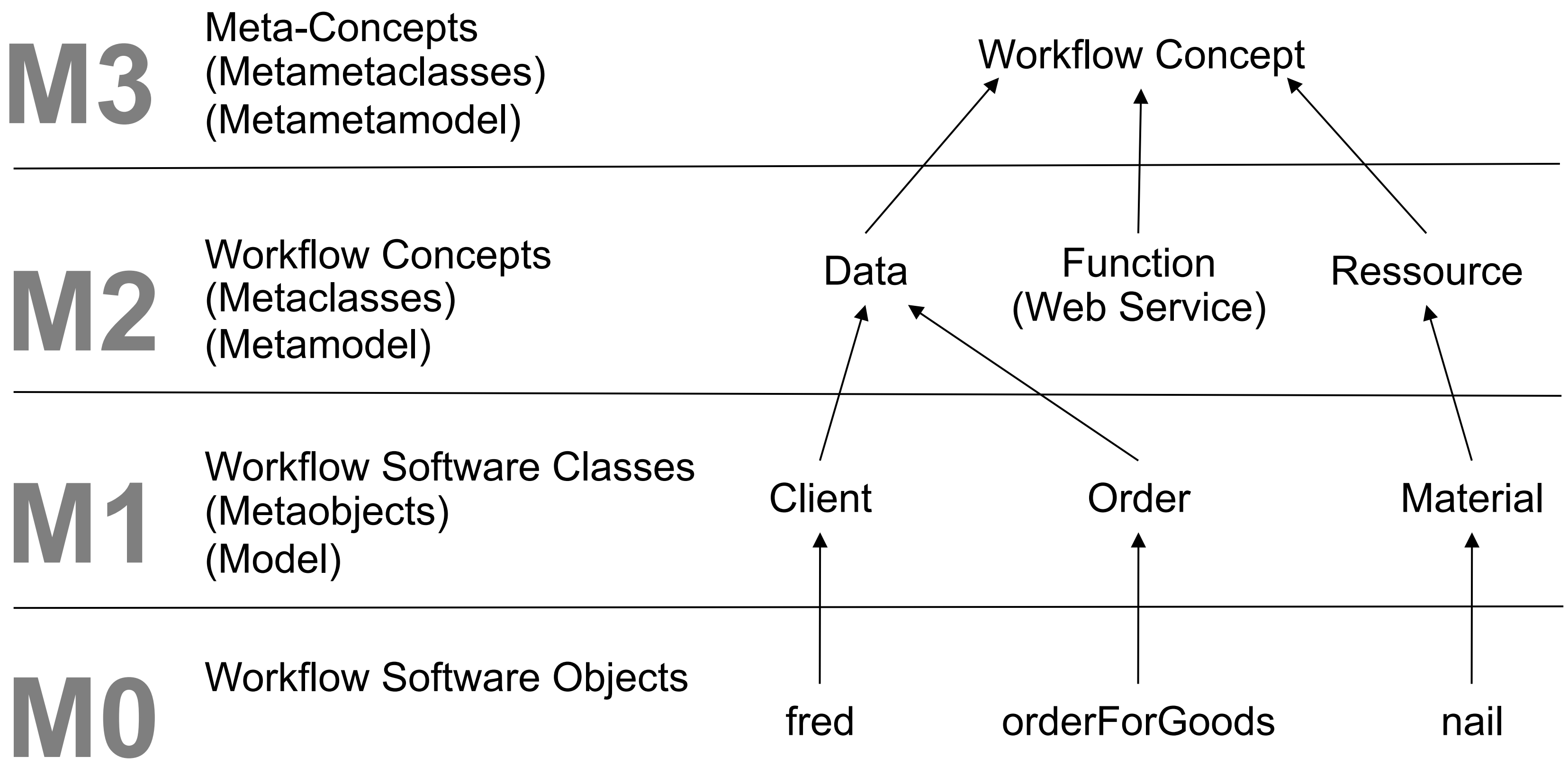
Use of Metamodels and Metaprogramming

To model, describe, introspect, and manipulate all sorts of objects, models, and languages:

- UML
- Workflow systems
- Databases (Common Warehouse Model, CWM)
- Programming languages
- Component systems, such as CORBA
- Composition systems, such as Invasive Software Composition
- ... probably all systems...

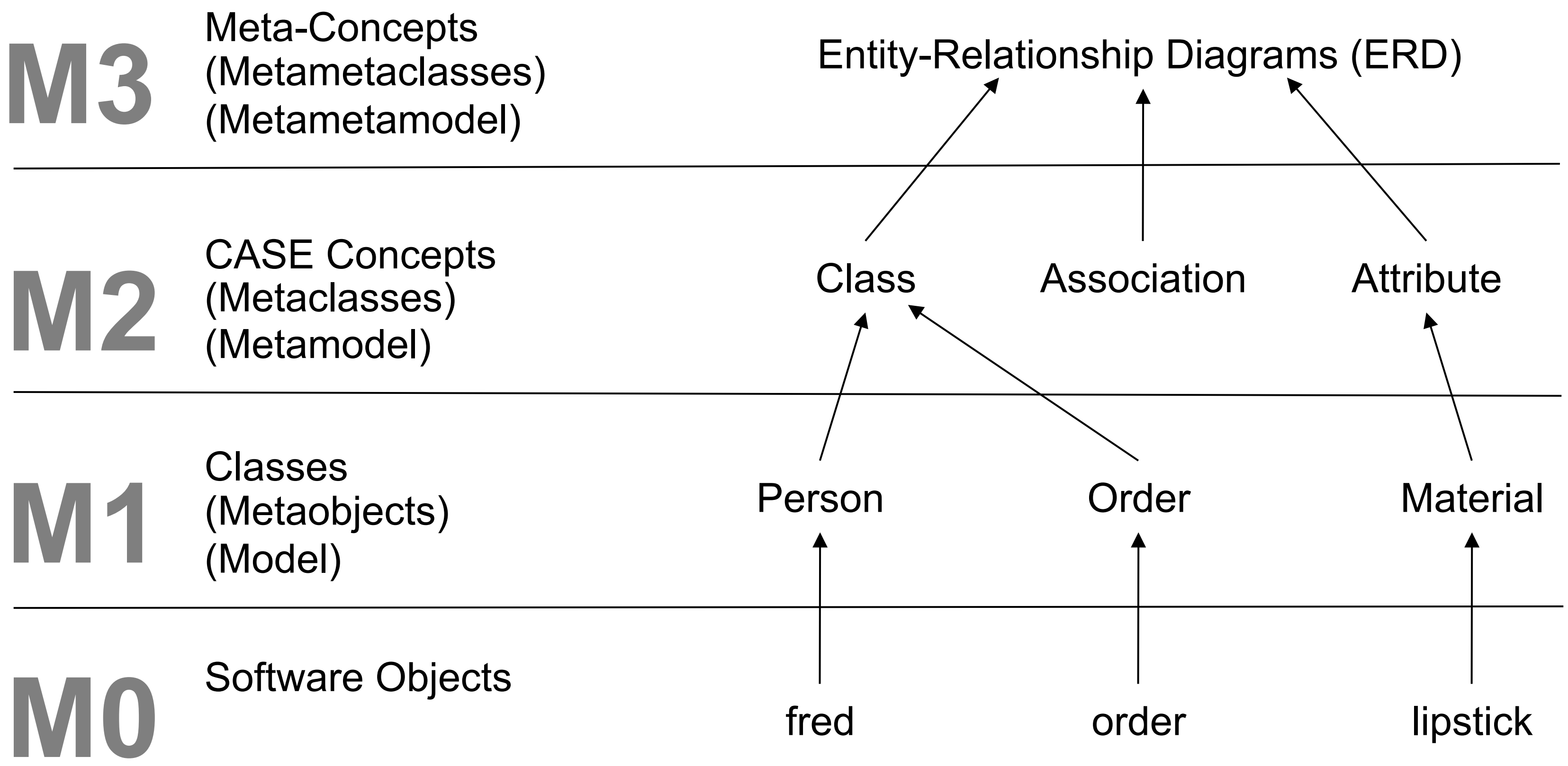
Metapyramid in Workflow Systems and Web Services (e.g., BPEL, BPMN)

- It is possible to specify workflow languages with the metamodelling hierarchy
- BPEL and other workflow languages can be metamodeled



Metapyramid CASE Data Interchange Format (CDIF)

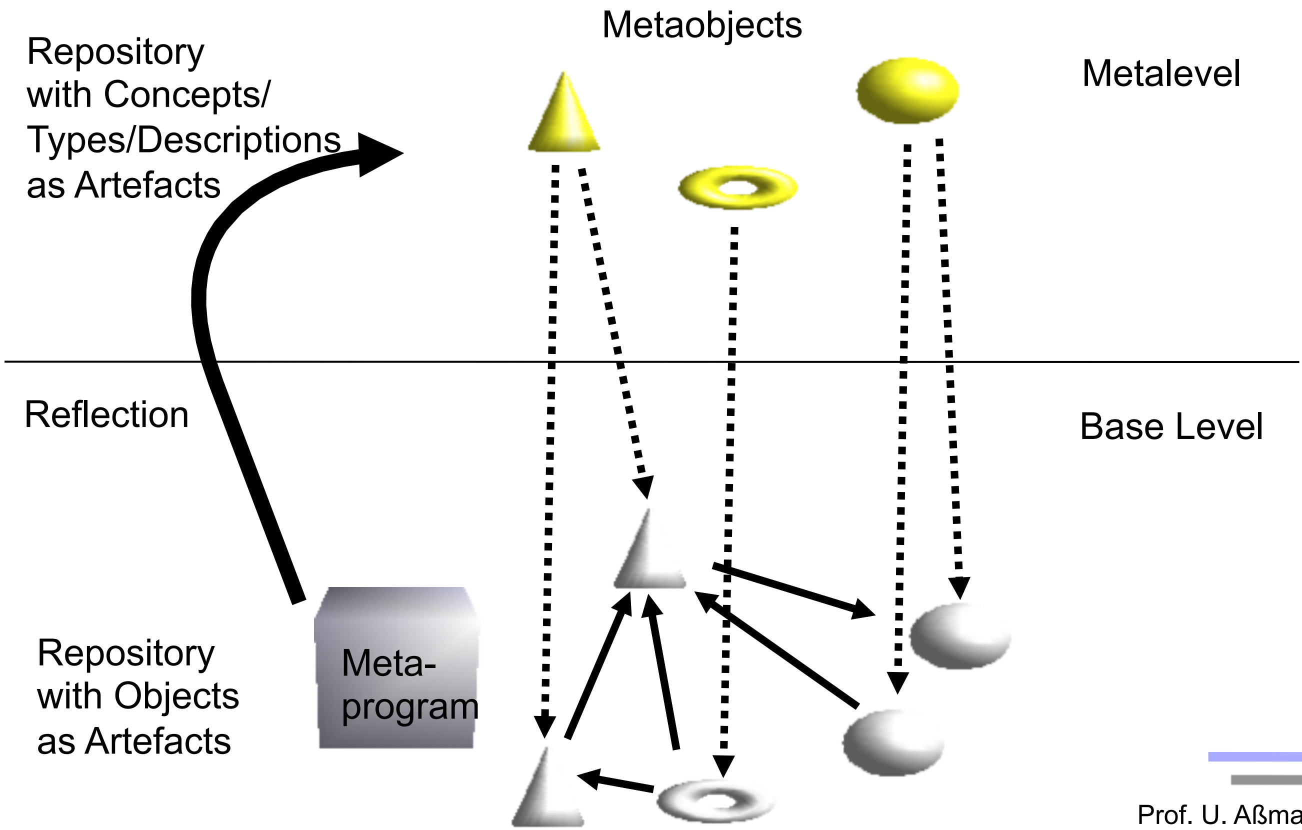
CDIF uses entities and relationships on M3 to model CASE concepts on M2



11.3 Metalevel Architectures

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
- Metaprogramming is programming with metaobjects



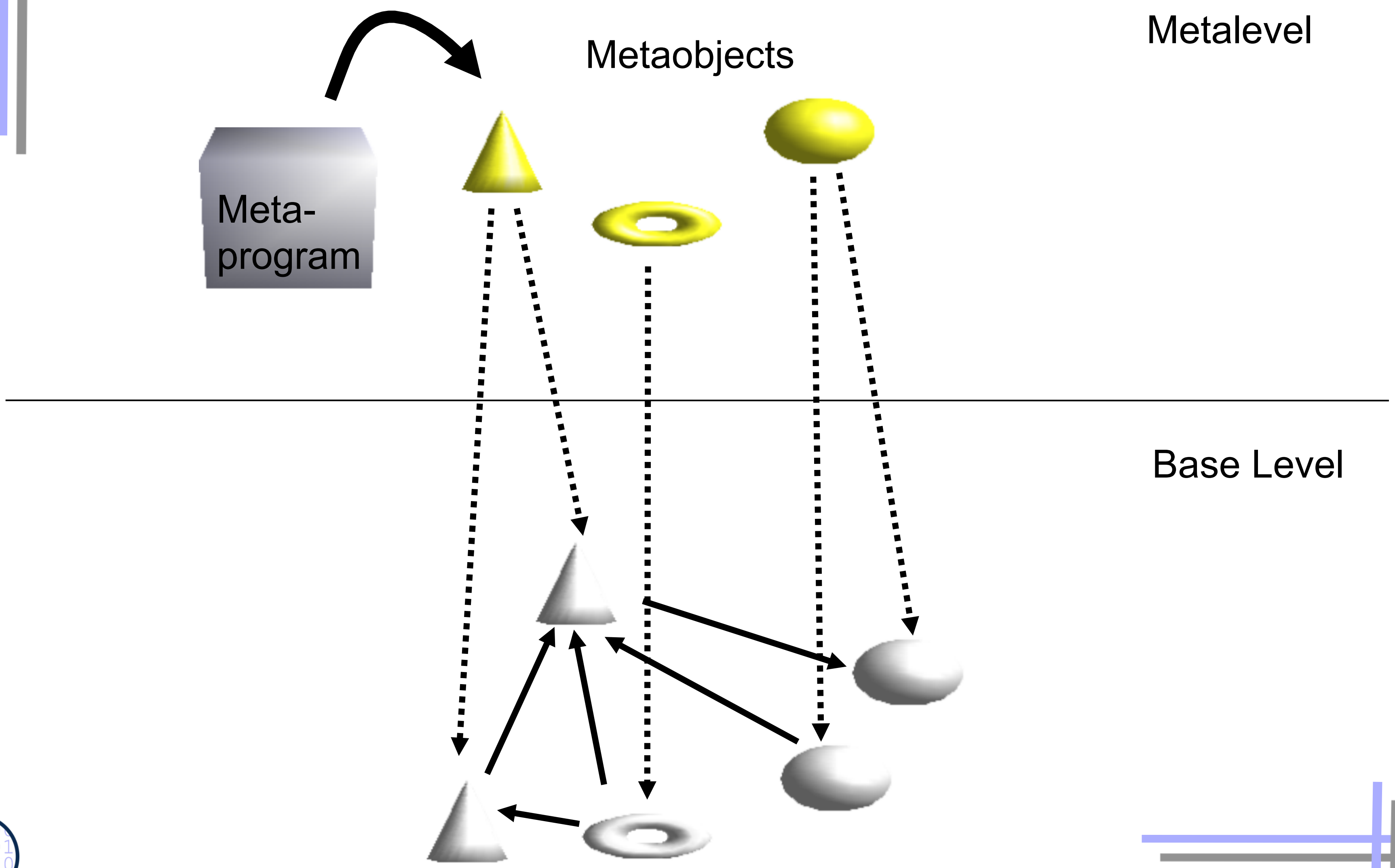
Examples

- 24/7 systems with total availability
  - Dynamic update of new versions of classes
  - Telecommunication systems
  - Power plant control software
  - Internet banking software
- Self-adaptive systems
  - Systems reflect about the context *and* themselves and, consequently, change themselves
- Reflection is used to think about versions of the systems
  - Keeping two versions at a time

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.
  - supports metaprogramming, but not full reflection
- Special variants that *separate* the metaprogram from the base level programs
  - *Introspective architecture* (no self modification)
  - *Staged metalevel architecture* (metaprogram evaluation time is different from system runtime)

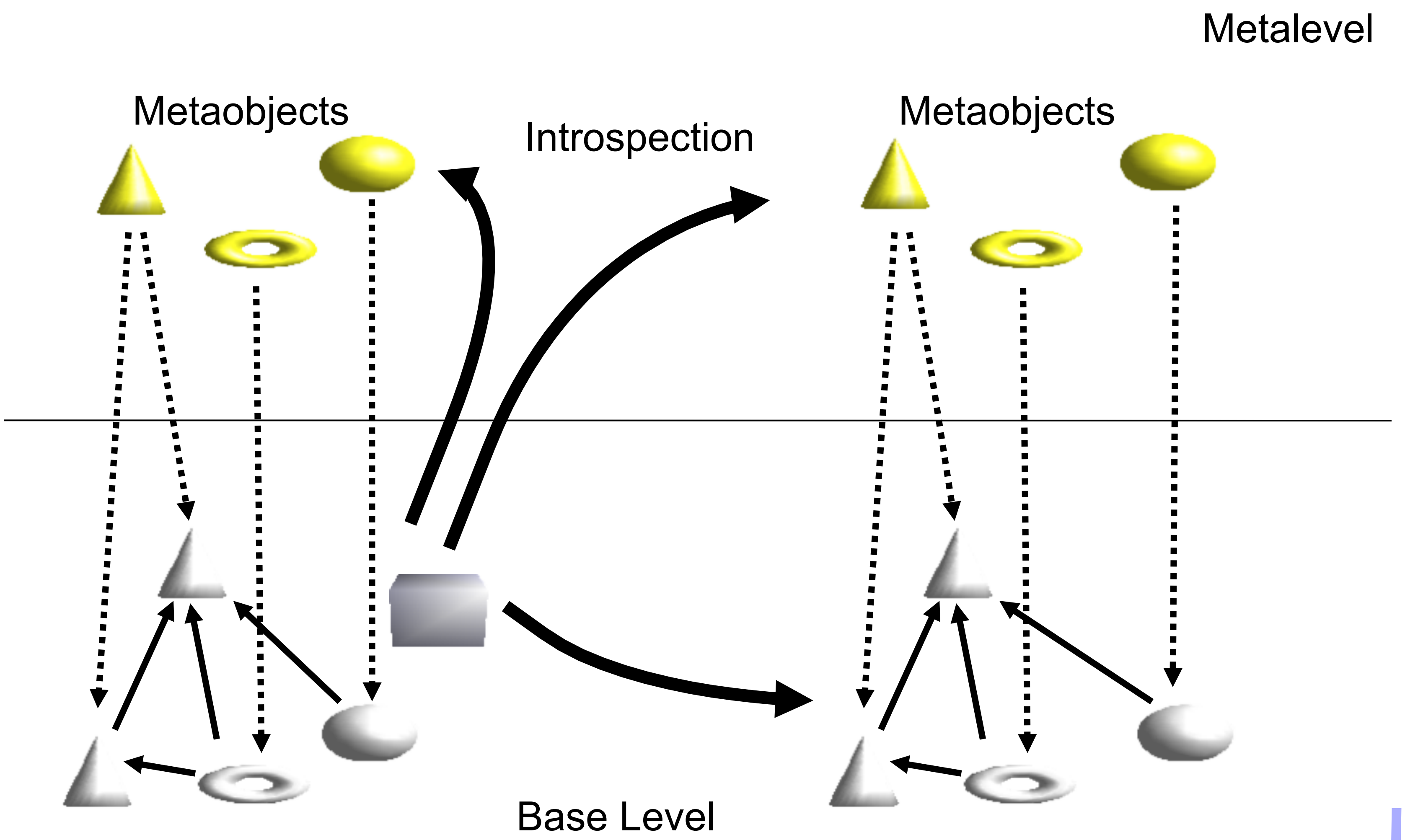
Metalevel Architecture



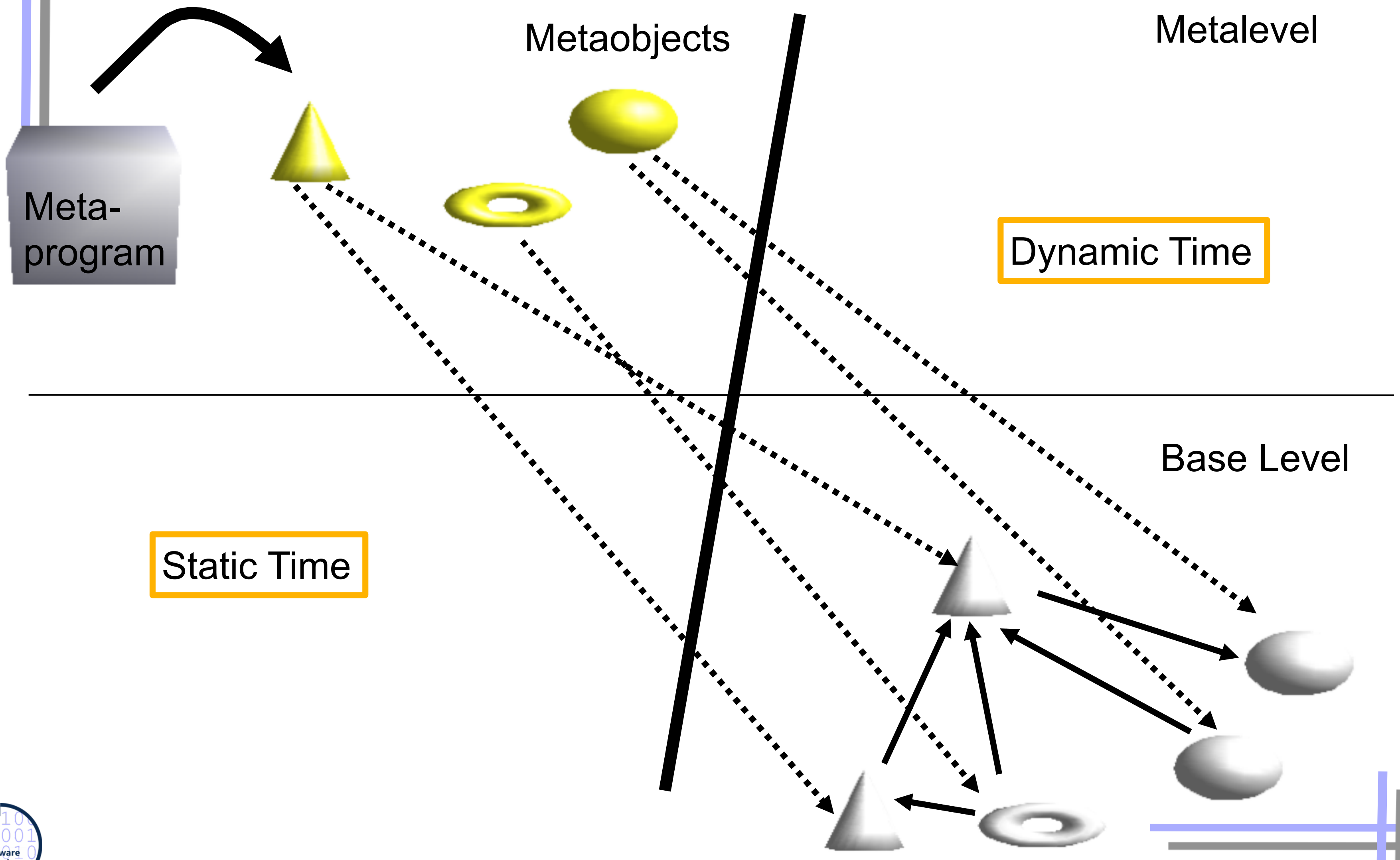
Examples

- Integrated development environment
  - Refactoring engine
  - Code generators
  - Metric analyzers (introspective)

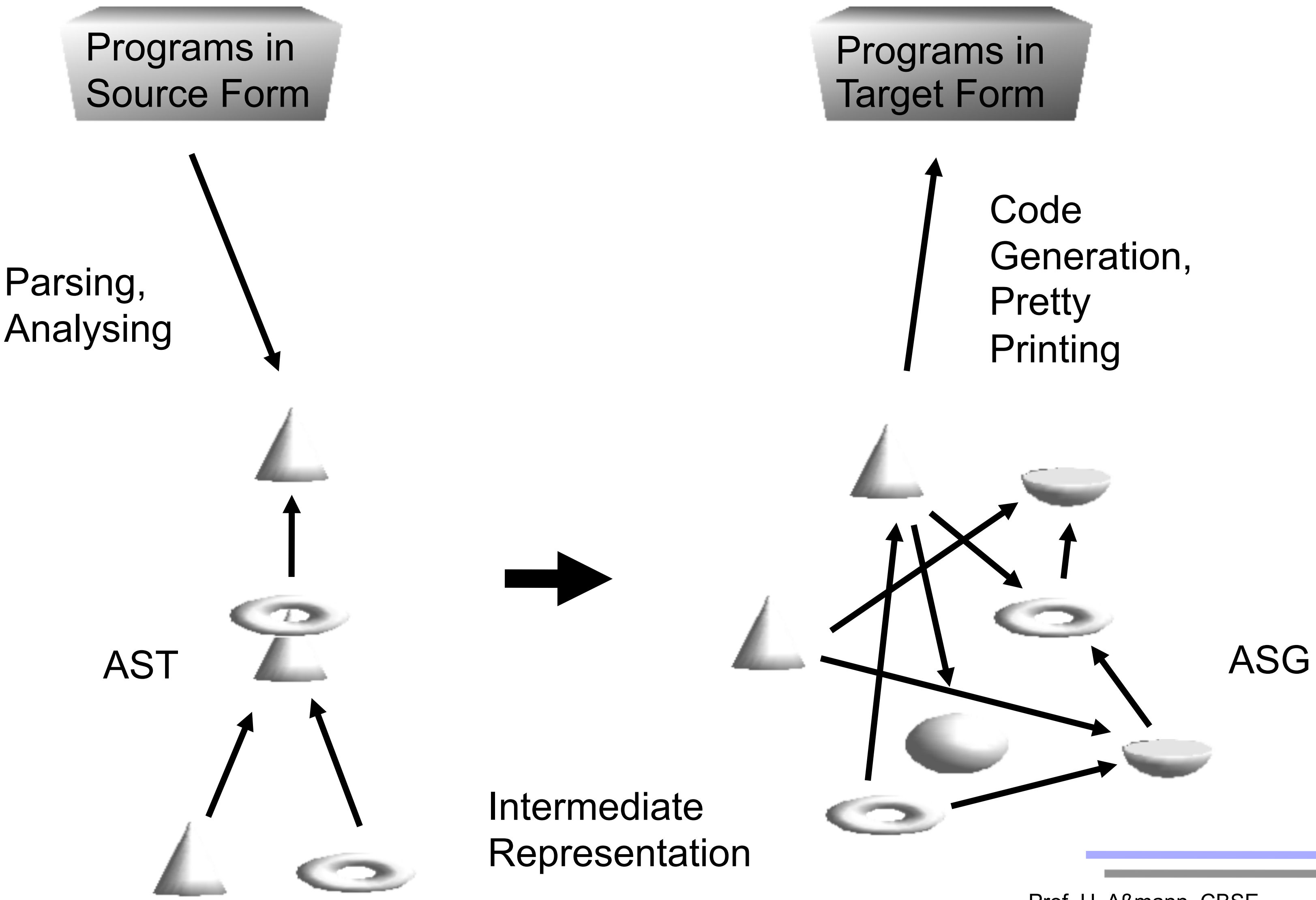
Introspective Architectures



Staged Metalevel Architecture (Static Metaprogramming Architecture)

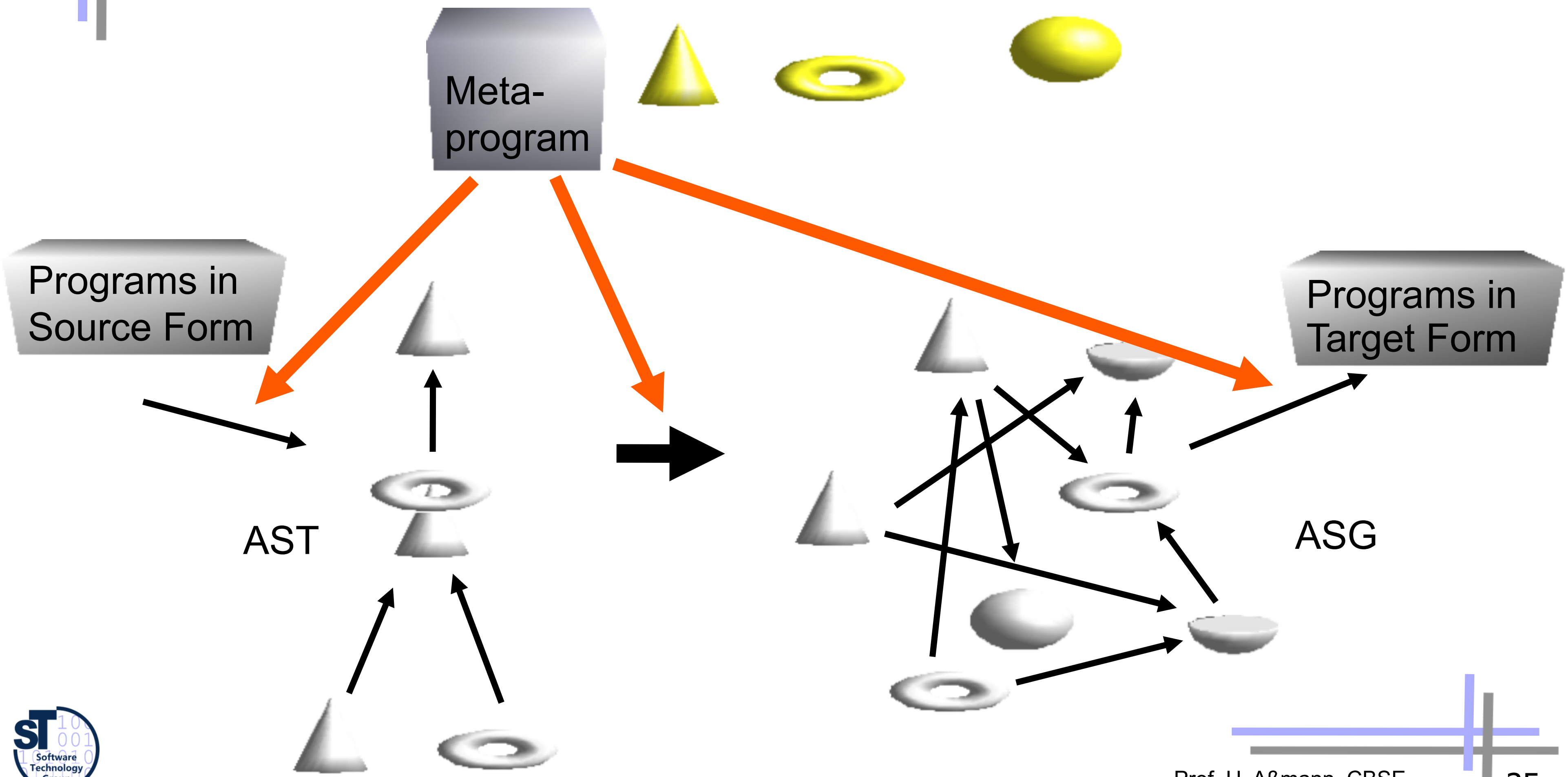


Compilers



Programs in Source Form
Programs in Target Form
Parsing, Analysing
Code Generation, Pretty Printing
AST
ASG
Intermediate Representation

Compilers Are Static Metaprograms



11.4 Metaobject Protocols (MOP)

Metaobject Protocol (MOP)

A **meta-object protocol (MOP)** is a reflective implementation of the methods of the metaclasses (**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 *(MOP intercession),* the language semantics is changed
  - or adapted to a context
  - If the MOP language is object-oriented, default implementations of metaclass methods can be overwritten by subclassing
  - and the semantics of the language is changed by subclassing
- By changing the MOP of a component from a component supermarket, the component can be adapted to the reuse context

A Very Simple MOP

```
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() { ... }
}
```

Adapting a Metaclass in a MOP By Subclassing

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

```
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[]{});
```

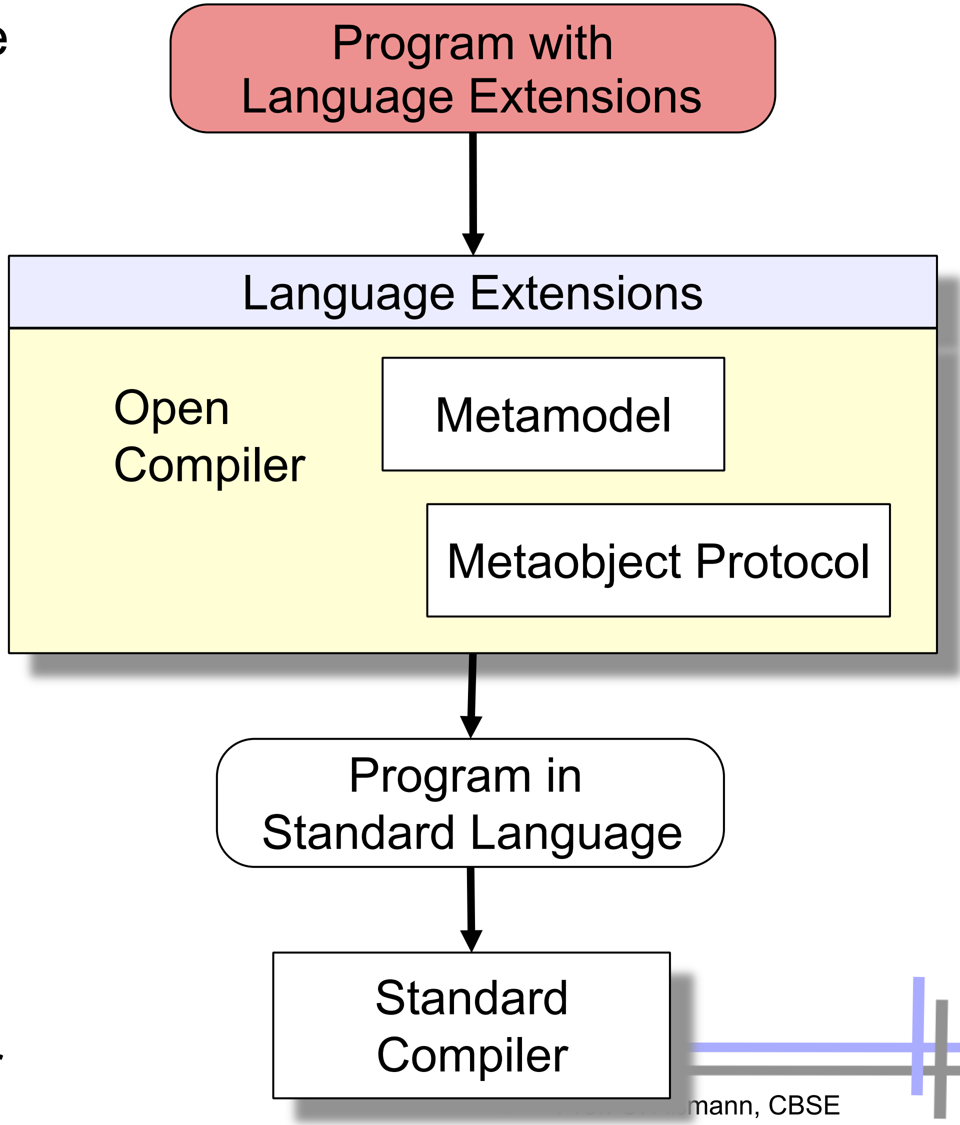
```
Here I am, accessing attribute place1
I am leaving attribute place1: value is WorkPiece #5
```

Adaptation of Components by MOP Adaptation

```
// Adapter is hidden in enterMethod
Method EventAdapterMethod extends Method {
  Object piece;

  public Object execute() {
    // event communication
    notifyRotaryTable();
    piece = listenToRotaryTable();

    super.execute();
    return piece;
  }
}
// Create a class Robot with the new semantics for takeUp()
Class Robot = new Class(new Attribute[]{ },
  new Method[]{ new EventAdapterMethod("takeUp") });
```

An Open Language has a Static MOP

- An **Open Language** has a static metalevel architecture (static metaprogramming architecture), with a *static MOP*
- ... offers its AST as metamodel for static metaprogramming
  - 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



An Open Language

- ... can be used to adapt components from a supermarket at compile time
  - During reuse of the component in system generation
  - Static adaptation of components
- Metaprograms are removed during system generation, no runtime overhead
  - Avoids the overhead of dynamic metaprogramming
- Ex.:. Open Java, Open C++

11.5 Metaobject Facility (MOF)

.. A structural metalanguage for graphs

.. of OMG

Metaobject Facility (MOF)

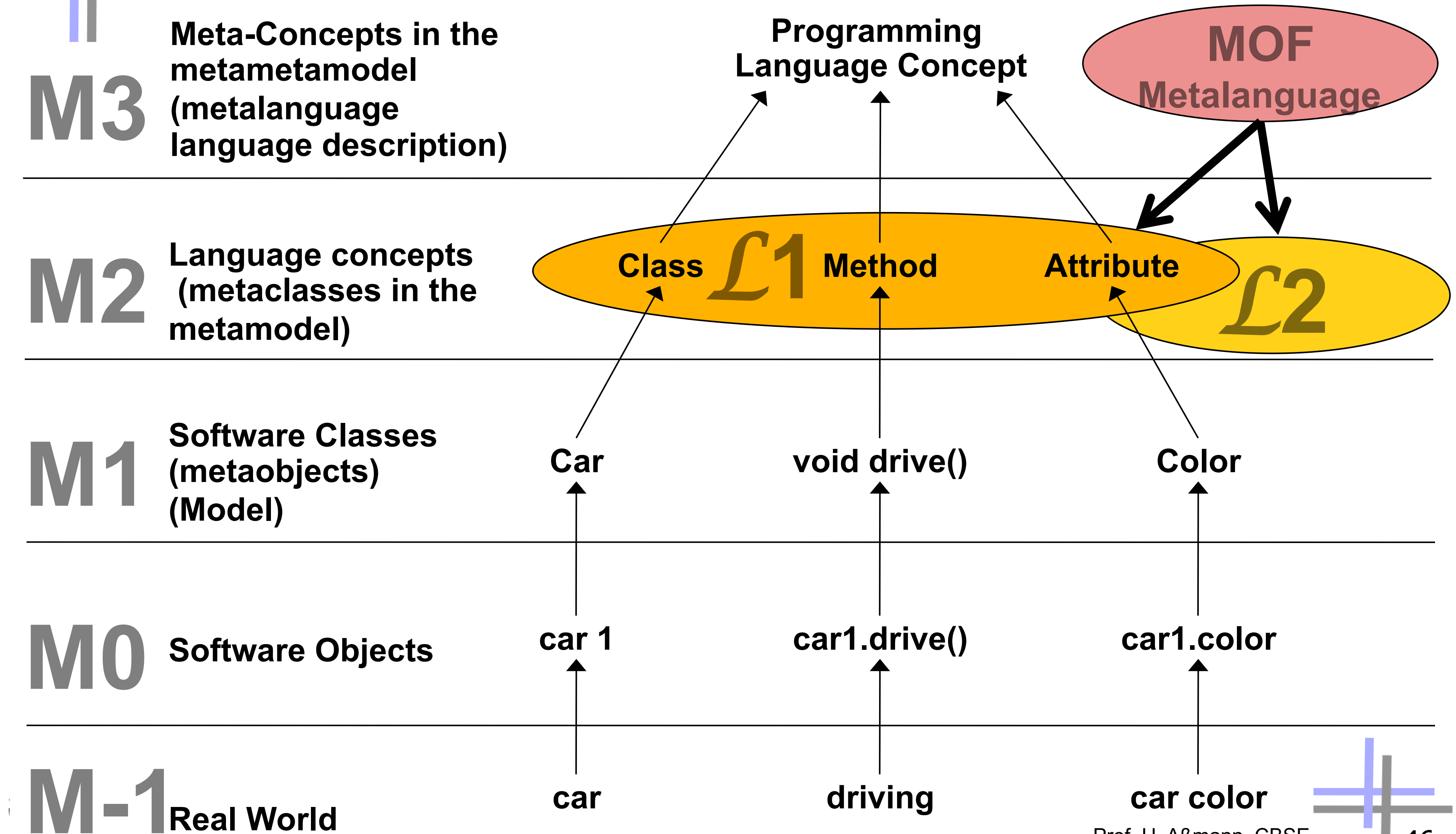
- Rpt: A metalanguage (on M3) is used to describe structural aspects of graph languages (on M2)
  - Context-free structure (model trees or abstract syntax trees, AST)
  - Context-sensitive structure and constraints (model graphs or abstract syntax graphs, ASG)
  - Dynamic semantics (behavior)

A **metaobject facility (MOF)** is a language specification language (*metalanguage*) to describe the context-free structure and context-sensitive *structure* of a language, to check the wellformedness of models.
Dynamic semantics (interpretation) is omitted.

Metaobject Facility (MOF)

- MOF (metaobject facility) of OMG is a metalanguage to describe the structure of modelling languages, and finally the structure of models as abstract syntax graphs (ASG)
  - MOF was first standardized Nov. 97, available now in version 2.0 since Jan 2006
- MOF is a mimimal UML class diagram like language
  - MOF provides the modeling concepts classes, inheritance, relations, attributes, signatures, packages; method bodies are lacking
  - Logic constraints (in OCL) on the classes and their relations
- A MOF is not a MOP
  - The MOP is interpretative
  - A MOF specification does not describe an interpreter for the full-fledged language, but provides only a *structural description*
  - The MOF specification is generative

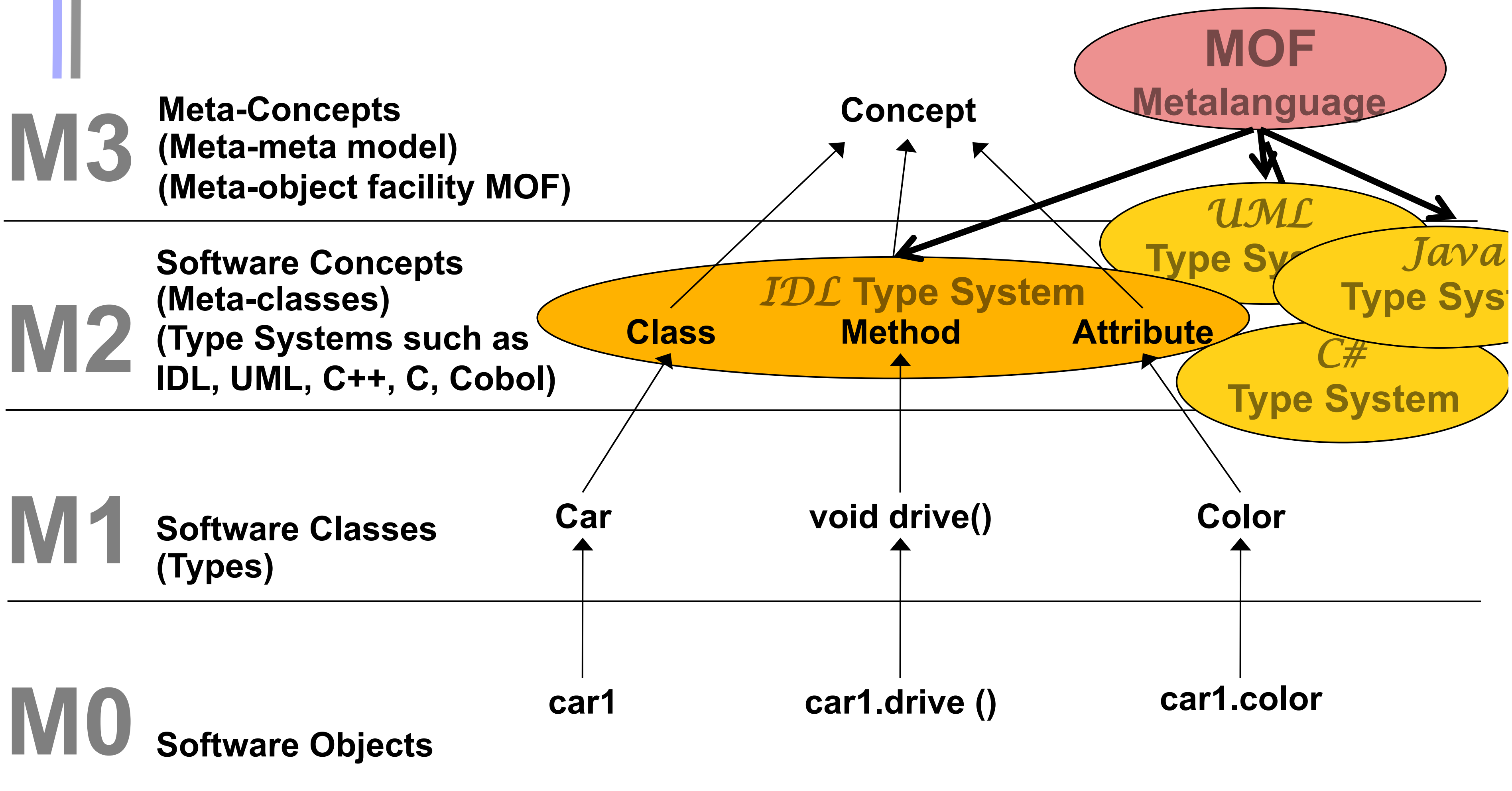
MOF Describes, Constrains, and Generates Structure of Languages on M2



MOF

- A MOF specification (a MOF metamodel) is a typed attributed graph, containing
  - the concepts of a language as metaclasses
  - Their relationships as associations between metaclasses
  - Their constraints
- With MOF, context-sensitive structure of languages are described, constrained, and generated
  - **Type systems**
    - to navigate in data with unknown types
    - to generate data with unknown types
    - Describing IDL, the CORBA type system
    - Describing XML schema
  - **Modelling languages** (such as UML)
  - **Relational schema language** (common warehouse model, CWM)
  - **Component models**
  - **Workflow languages**

Describing Type Systems with the MOF



Meta-meta-models describe general type systems!

A Typical Application of MOF: Mapping Type Systems with a Language Mapping

- The type system of CORBA-IDL is a kind of “mediating type system” (least common denominator)
  - Maps to other language type systems (Java, C++, C#, etc)
  - For interoperability to components written in other languages, an interface description in IDL is required
- Problem: How to generate Java from IDL?
  - You would like to say (by introspection):

```
for all c in classes_in_IDL_spec do
        generate_class_start_in_Java(c);
        for all a in c.attributes do
            generate_attribute_in_Java(a);
        done;
        generate_class_end_in_Java(c);
done;
```

- Other problems:
  - How to generate code for exchange between C++ and Java?
  - How to exchange data of OMT and UML-based CASE-tools?
  - How to bind other type systems as IDL into Corba (UML, ...)?

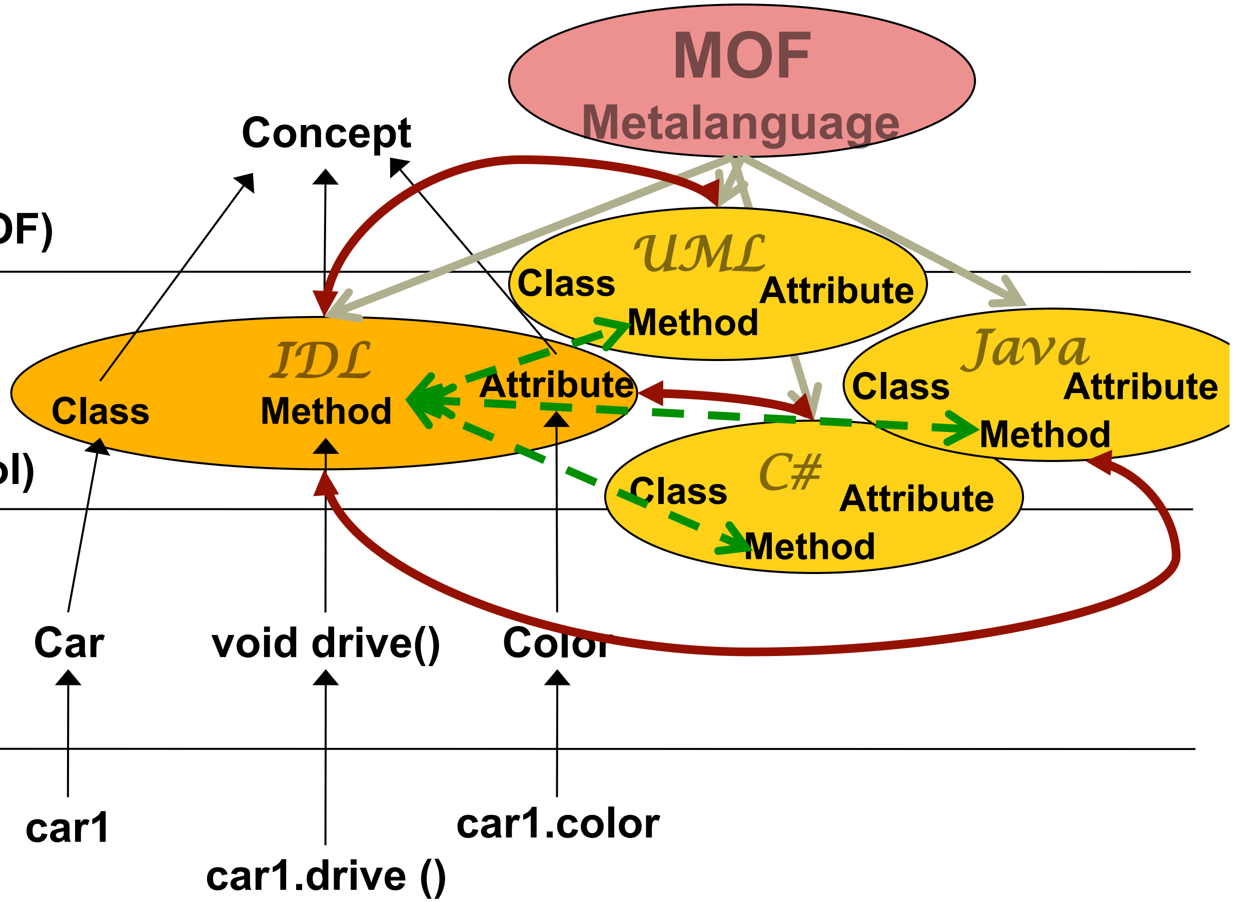
Mapping Type Systems in CORBA

M3 **Meta-Concepts (Meta-meta model) (Meta-object facility MOF)**

M2 **Software Concepts (Meta-classes) (Type Systems such as IDL, UML, C++, C, Cobol)**

M1 **Software Classes (Types)**

M0 **Software Objects**



Meta-meta-models describe general type systems!

Automatic Data Transformation with the Metaobject Facility (MOF)

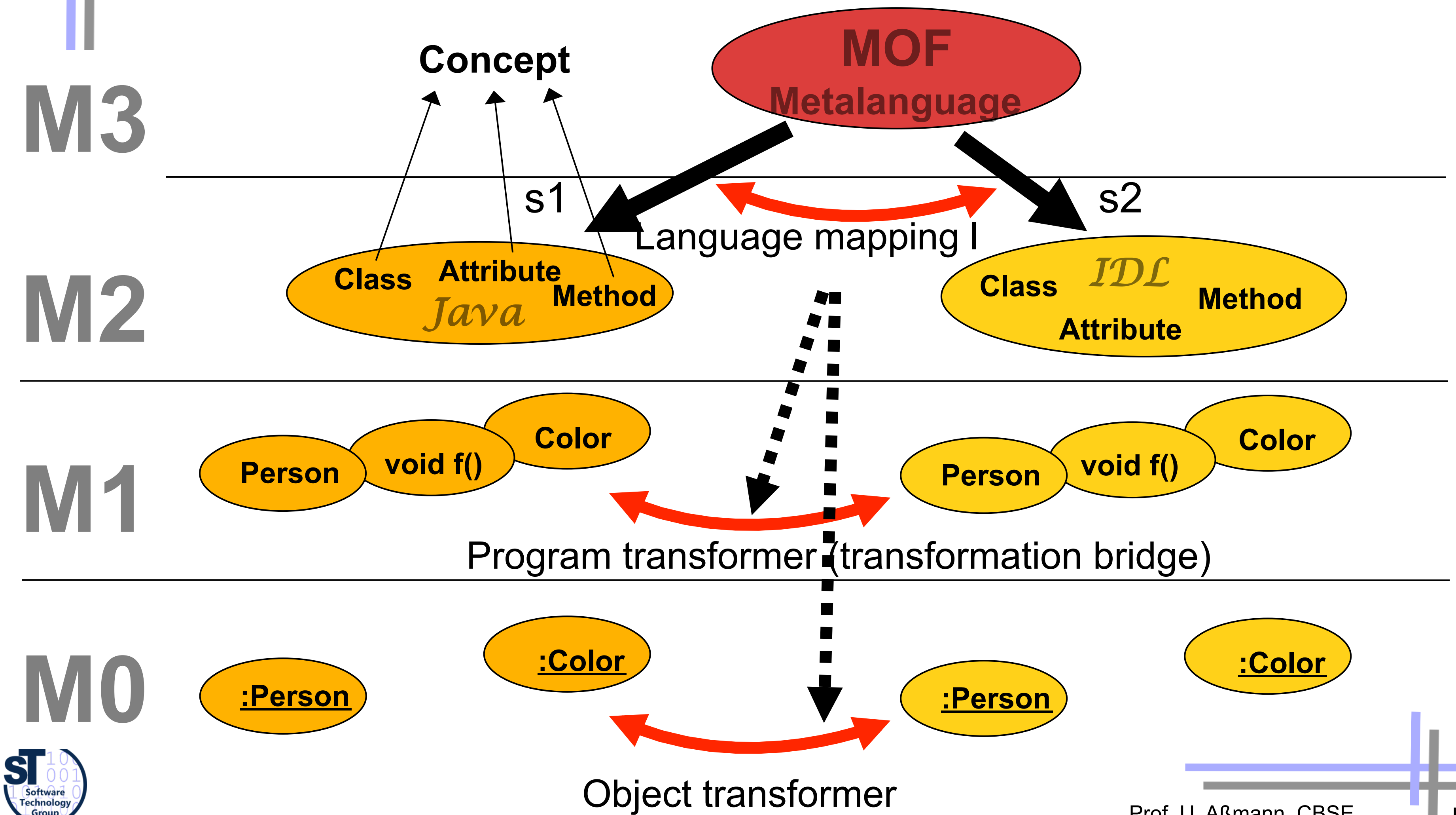
- From two MOF metamodels, **transformation bridges** are generated
  - And an isomorphic mapping between them
- Transformer functionality can be generated
  - Data fitting to MOF-described type systems can automatically be transformed into each other
  - The mapping is only an isomorphic function in the metametamodel
  - Exchange data between tools possible
- Code looks like (similarly for all mapped languages):

```
for all c in classes in Java_spec do
       generate_class_mapper_from_Java_To_IDL(c);
       for all a in c.attributes do
           generate_attribute_mapper_from_Java_To_IDL(a);
       done;
       generate_class_end_mapper_from_Java_To_IDL(c);
done;
```

```
for all c in classes in IDL_spec do
       generate_class_mapper_from_IDL_to_C++(c);
       for all a in c.attributes do
           generate_attribute_mapper_from_IDL_to_C++ (a);
       done;
       generate_class_end_mapper_from_IDL_to_C++ (c);
done;
```

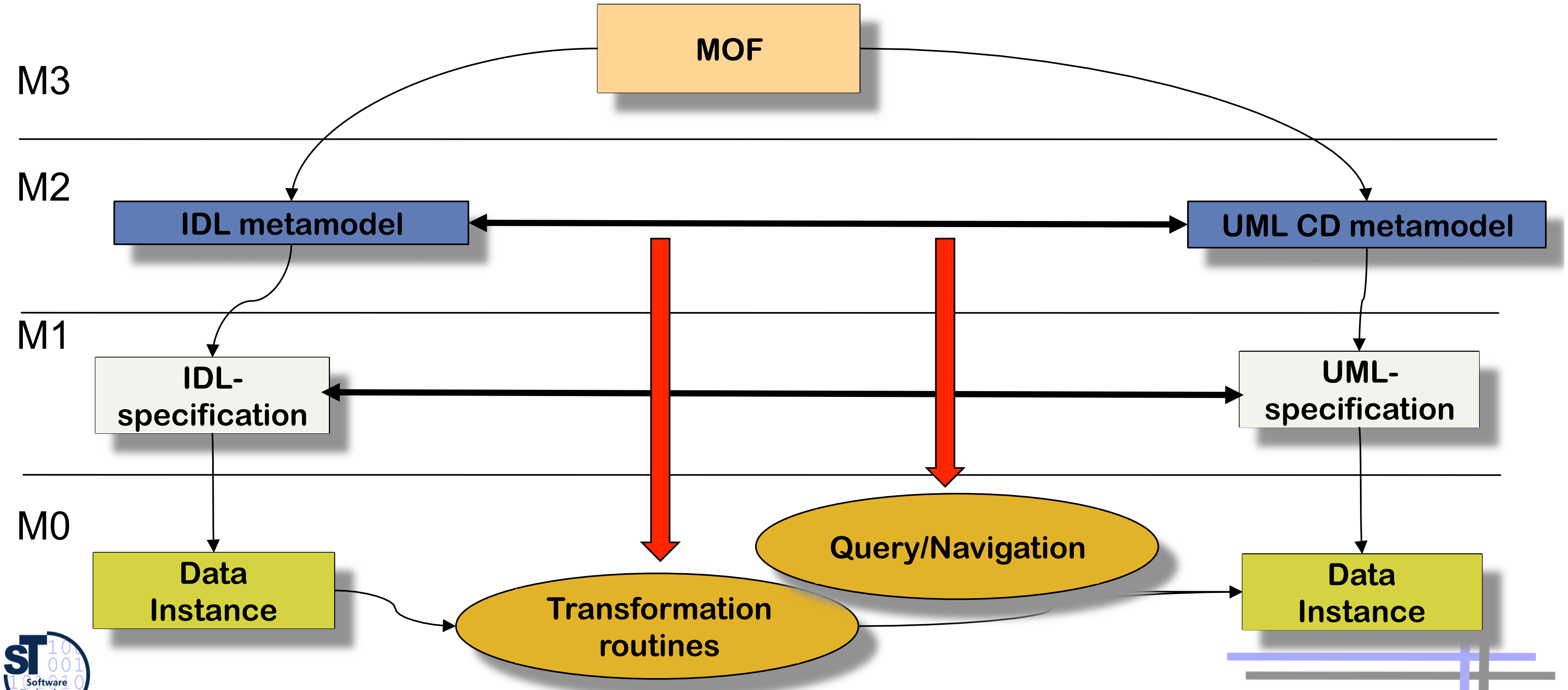
Language Mappings for Program and Object Mappings

- Comparing the MOF metamodels s1 and s2 with a language mapping l, transformers on classes and objects can be generated



The MOF as Smallest Common Denominator and "Mediator" between Type Systems

- From the mappings of the language-specific metamodels to the IDL metamodel, transformation, query, navigation routines can be generated
- More in course "Softwarewerkzeuge"



Bootstrap of MOF

- MOF is specified in itsel (self-describing, lifted metamodel)
  - The structure, relations and constraints of the MOF language can be described with itself
- The MOF can be bootstrapped with the MOF
- IDL for the MOF can be generated
  - With this mechanism the MOF can be accessed as remote objects from other languages
  - MOF descriptions can be exchanged
  - Code for foreign tools be generated from the MOF specifications
  - The MOF-IDL forms the interface for *metadata repositories (MDR)* http://mdr.netbeans.org
  - Engines in any IDL-mapped language can access an MDR, by using the IDL-generated glue code
  - Example: OCL Toolkit Dresden (which also supports EMF/Ecore besides of MDR)

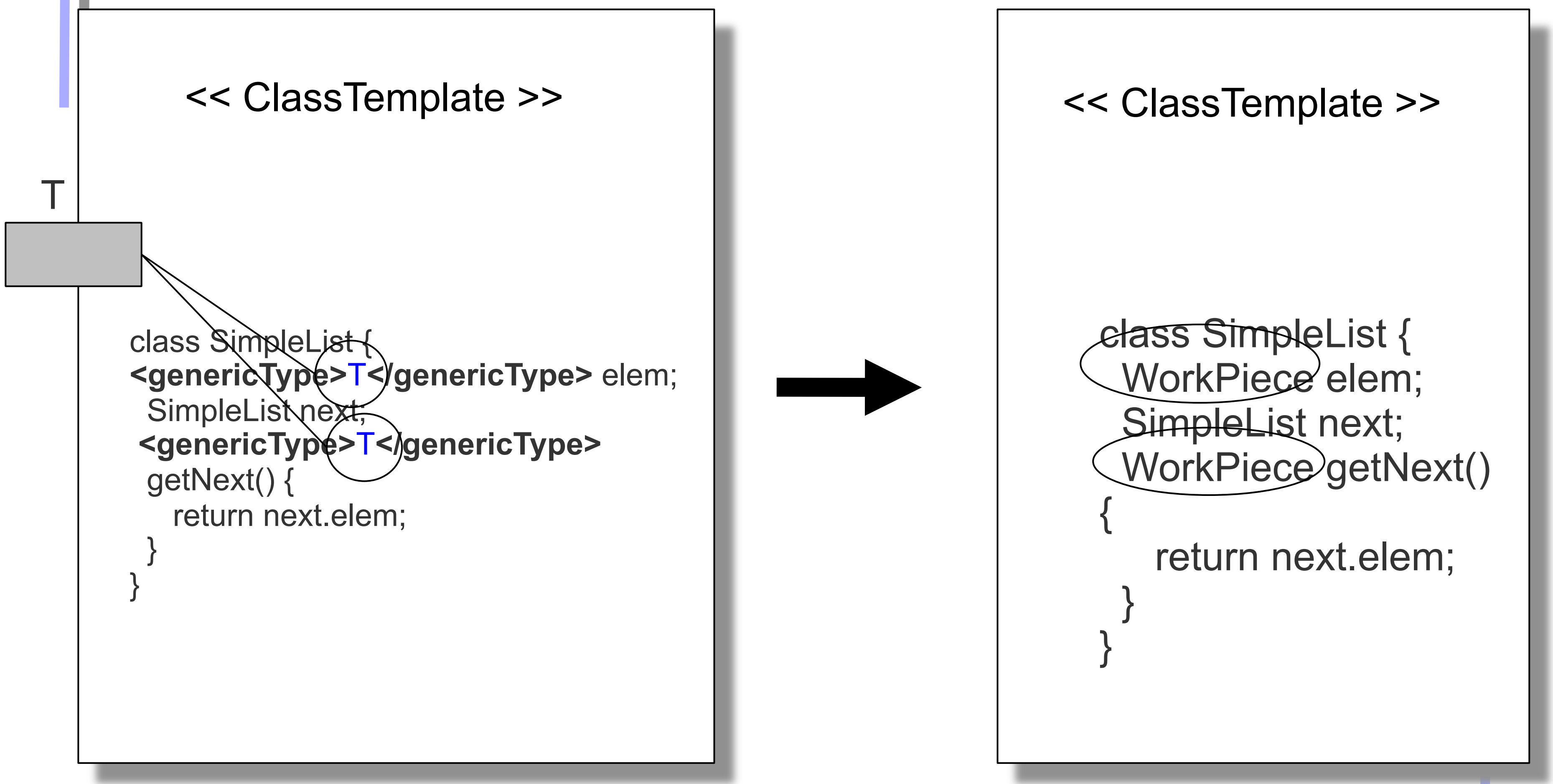
Summary MOF

- The MOF describes the structure of a language
  - Type systems
  - Languages
  - itself
- Relations between type systems are supported
  - For interoperability between type systems and -repositories
  - Automatic generation of mappings on M2 and M1
- Reflection/introspection supported
- Application to workflows, data bases, groupware, business processes, data warehouses

11.6 Asserting Embedded Metadata with Component Markup

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

Example: Generic Types with XML Markup



Markup Languages

- Markup languages convey more semantics for the artifact they markup
  - For a component, they describe metadata
  - XML, SGML are markup languages
- A markup can offer contents of the component for the external world, i.e., for composition
  - Remember: a component is a container
  - It can offer the content for introspection
  - Or even introcession
- A markup is stored together with the components, not separated

Embedded and Exbedded Markup

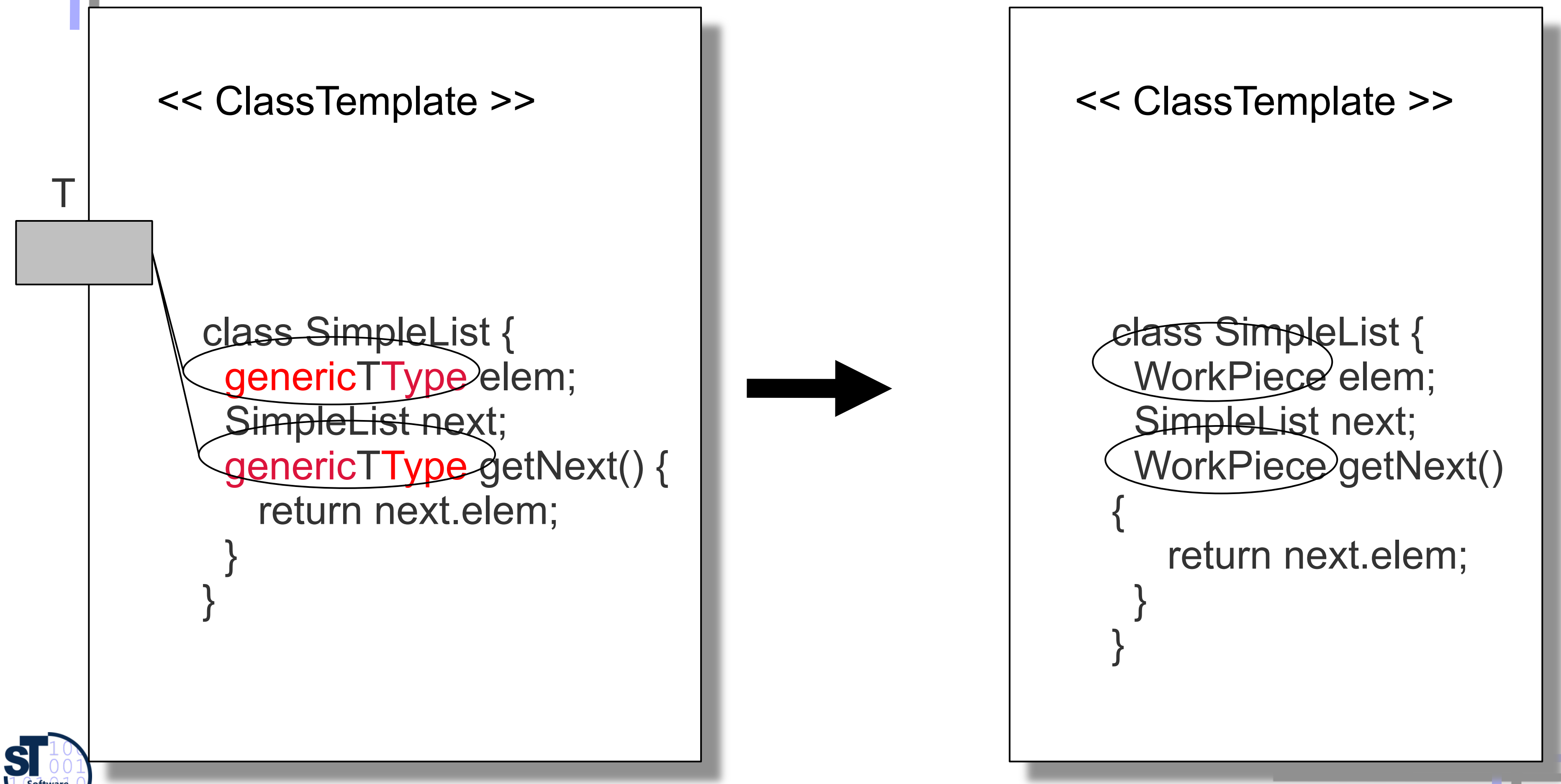
- Similarly to embedded and exbedded links, markup can be defined as *embedded* or *exbedded (style sheets)*
  - Embedded markup marks (types) a part of a component in-line
    - The part may be required or provided
  - Exbedded markup (style sheets) marks (types) a part of a component off-line
    - with a matching language that filters the document contents
    - with adressing that points into the component
    - positions
    - implicit hook names
    - adress expressions on compound components
- Some component languages allow for defining embedded markup
  - latex (new environments and commands)
  - languages with comments (comment markup)
- Exbedded markup (style sheets) can refer to embedded markup
- Embedded and exbedded Markup Can Be Mixed

Markup with Hungarian Notation

- **Hungarian notation** is a embedded 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 be used
- The composition environment can ask about the names in the interfaces of a component (introspection)
  - and can deduce more semantics

Generic Types with Hungarian Notation

Hungarian notation has the advantage, that the syntactic tools of the base language work for the generic components, too



Java Beans Naming Schemes use Hungarian Notation

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

Markup and Metadata Attributes

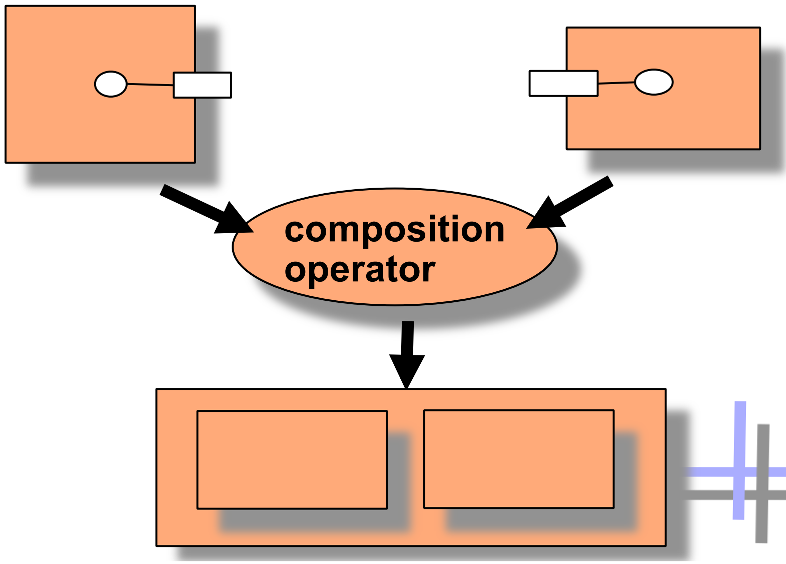
Many languages support *metadata attributes*

- by Structured Comments
  - Javadoc tags
    - **`@author  @date  @deprecated  @entity  @invoke-around`**
- Java annotations and C# attributes are *metadata*
  - Java annotations:
    - **`@Override  @Deprecated  @SuppressWarnings`**
  - C# /.NET attributes
    - **`[author(Uwe Assmann)]`**
    - **`[date Feb 24]`**
    - **`[selfDefinedData(...)]`**
  - User can define their own metadata attributes themselves
  - Metadata attributes are compiled to byte code and can be inspected by tools of an IDE, e.g., linkers, refactorers, loaders
- UML stereotypes and tagged values
  - <<Account>> { author=”Uwe Assmann” }

Markup is Essential for Component Composition

- because it supports introspection and intercession
  - 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 have some form of reflective architecture!

- Composition operators need to know where to compose
- Markup marks the variation points and extension points of components
- The composition operators introspect the components
- And compose



What Have We Learned?

- Metalanguages are important (M3 level)
  - Reflection is modification of oneself
  - Introspection is thinking about oneself, but not modifying
  - Metaprogramming is programming with metaobjects
  - There are several general types of reflective architectures
- A MOP can describe an interpreter for a language; the language is modified if the MOP is changed
  - A MOF specification describes the structure of a language
  - The CORBA MOF is a MOF for type systems mainly
- Component and composition systems are reflective architectures
  - Markup marks the variation and extension points of components
  - Composition introspects the markup
  - Composition can also use static metaprogramming or open languages

The End