TDDD05 / DF14900
Component-Based Software

Metamodeling and Metaprogramming

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Some slides by courtesy of U. Assmann, IDA / TU Dresden

1. Introduction to metalevels
2. Different Ways of Metaprogramming
3. UML Metamodel and MOF
4. Component markup

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

Metadata

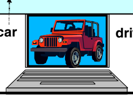
- **Meta**: means "describing"
- **Metadata**: describing data (sometimes: self-describing data).
  - The language (esp., type system) for specifying metadata is called **metamodel**.
- **Metalevel**: the elements of the meta-level (the meta-objects) describe the objects on the base level
- **Metamodeling**: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

Metadata — Meta level, Concepts level

Data, Code, Information — Base level

Metalevels in Programming Languages

Level			
Level 3 - Meta-Concepts in the metameta model, the metalanguage (language description)	Programming Language Concept		
Level 2 - Language concepts (Metaclasses in the metamodel)	Class	Method	Attribute
Level 1 - Software Classes (meta-objects) (Model)	Car	void drive() {}	int color
Level 0 - Software Objects	car 1	car1.drive()	car1.color
"Real World" Entities	car	driving	car color



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Classes and Metaclasses

Classes in a software system

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

Metaclasses

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

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

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

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
- Enabled by reification of meta-objects at base level (e.g., as API)

Metadata — Meta level

Data, Code, Information — Base level

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).

Example: Creating a Class from a Metaclass

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

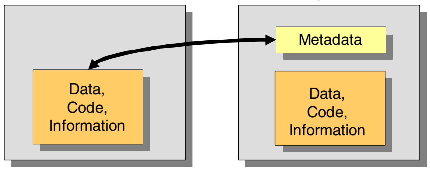
```
public class Class {
   Attribute[] fields;
   Method[] methods;
   Class ( Attribute[] f, Method[] m) {
     fields = f;
     methods = m;
   }
}
public class Attribute {..}
public class Method {..}
```

- Create a new class at runtime 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 ConveyorBelt = new Class( new Attribute[]{ "WorkPiece[] pieces" },  new Method[]{});
```

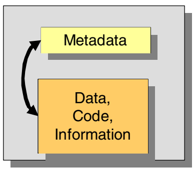

Introspection

- *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 for late (run-time) binding



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



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.

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)

Good for language extension / customization, e.g. with UML MOF, or for compiler generation

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

Use of Metamodels and Metaprogramming

To model, describe, introspect, and manipulate

- Programming languages, such as Java Reflection API
- Modeling languages, such as UML or Modelica
- XML
- Compilers
- Debuggers
- Component systems, such as JavaBeans or CORBA DII
- Composition systems, such as Invasive Software Composition
- Databases
- ... many other systems ...

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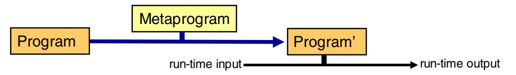
2. Different Ways of Metaprogramming

- meta-level vs. base level
- static vs. dynamic

Metaprograms are programs that compute about programs



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Metaprograms can run at base level or at meta level

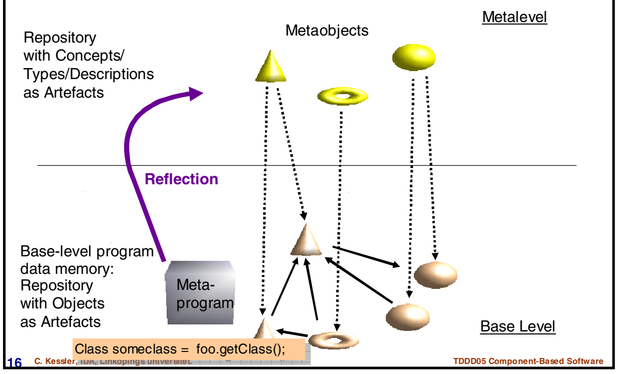
Metaprogram execution at the metalevel:

- Metaprogram is separate from base-level program
- Direct control of the metadata as metaprogram data structures
- Expression operators are defined directly on the metaobjects
- Example: Compiler, program analyzer, program transformer
  - Program metadata = the internal program representation
    - has classes to create objects describing base program classes, functions, statements, variables, constants, types etc.

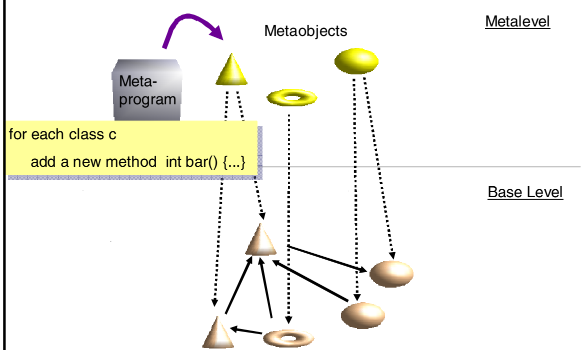
Metaprogram execution at the base level:

- Metaprogram/-code embedded into the base-level program
- All expressions etc. evaluated at base level
- Access to metadata only via special API, e.g. Java Reflection

Base-Level Metaprogram



Meta-level Metaprogram

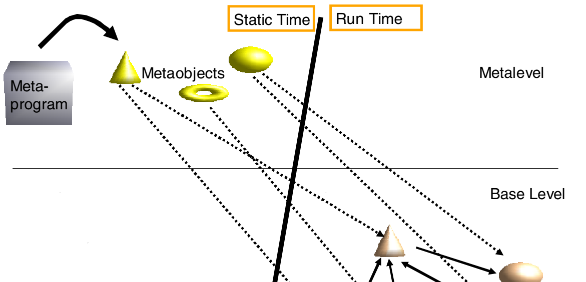


Static vs. Dynamic Metaprogramming

Recall: Metaprograms are programs that compute about programs.

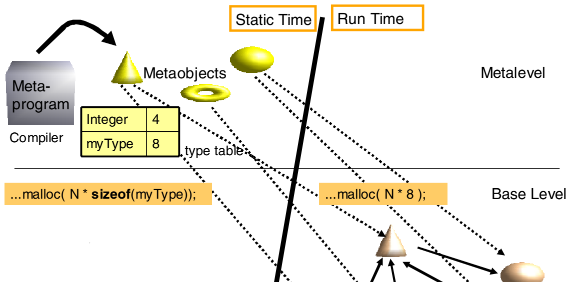
- **Static metaprograms**
  - Execute before runtime
  - Metainformation removed before execution – no runtime overhead
  - Examples: Program generators, compilers, static analyzers
- **Dynamic metaprograms**
  - Execute at runtime
  - Metadata stored and accessible during runtime
  - Examples:
    - Programs using reflection (Introspection, Intercession);
    - Interpreters, debuggers

Static Metaprogramming



Metaprogram and metaobjects
exist only at compile time.
No run-time overhead.

Example: Static Metaprogramming (1)



Metaprogram and metaobjects
exist only at compile time.
No run-time overhead.

Example: Static Metaprogramming (2)

C++ templates

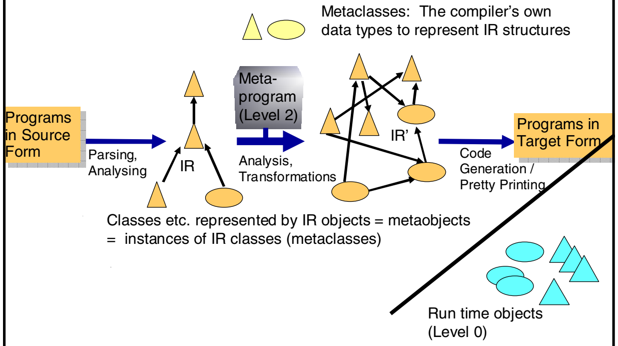
- Example: generic type definition
  - (Meta)Information about generic type removed after compiling!

```
template <class E>
class Vector {
  E *pelem;
  int size;
  E get( int index ) {...}
  ...
}
...
Vector<int> v1;
Vector<float> v2;
```

expanded at compile time to equivalent of:

```
class Vector_int {
  int *pelem;
  int size;
  int get( int index ) {...}
  ...
}
class Vector_float {
  float *pelem;
  int size;
  float get( int index ) {...}
  ...
}
...
Vector_int v1;
Vector_float v2;
```


Compilers Are Static Metaprograms



Compilers are Static Metaprograms

```
char x[7];
int a[13];
...
```

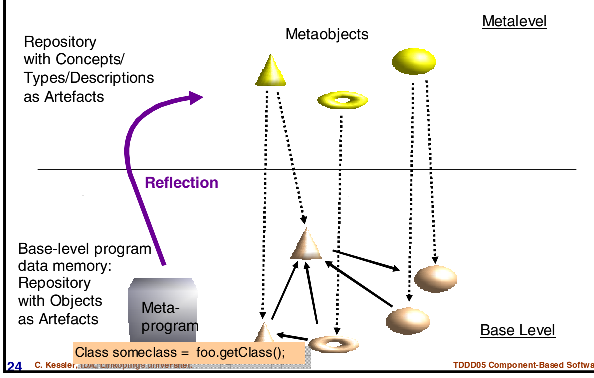
```
/* array - construct the type `array 0..n-1 of ty' with alignment a or ty's */
Type array( Type ty,  int n,  int a )
{
   if (ty && isfunc(ty)) {
      error( "illegal type `array of %t'\n", ty );
      return array ( inttype, n, 0 );
   }
   if (a == 0)
      a = ty->align;
   if (level > GLOBAL && isarray(ty) && ty->size == 0)
      error( "missing array size\n" );
   if (ty->size == 0) {
      if (unqual(ty) == voidtype)
         error( "illegal type `array of %t'\n", ty );
      else if (Aflag >= 2)
         warning( "declaring type `array of %t' is undefined\n", ty );
   } else if (n > INT_MAX / ty->size) {
      error( "size of `array of %t' exceeds %d bytes\n", ty, INT_MAX );
      n = 1;
   }
   return tynode ( ARRAY, ty, n * ty->size, a, (Generic)0 );
}
```

chartype	1
inttype	4
voidtype	0
ARRAY(7,chartype)	7
ARRAY(13,inttype)	52

type table excerpt

Source: lcc C compiler,
excerpt of file "types.c"
(type table management)

Dynamic Metaprogramming



Summary: Ways of Metaprogramming

Metaprogram runs at:	Base level	Meta level
Compile/Deployment time (static metaprogramming)	C++ template programs C sizeof(...) operator C preprocessor	Compiler transformations; COMPOST
Run time (dynamic metaprogramming)	Java Reflection JavaBeans introspection	Debugger

Reflection

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

3. UML Metamodel and MOF

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UML Metamodel and MOF

UML metamodel

- specifies UML semantics
- in the form of a (UML) class model (= reification)
- specified in UML Superstructure document (OMG 2006) using only elements provided in MOF

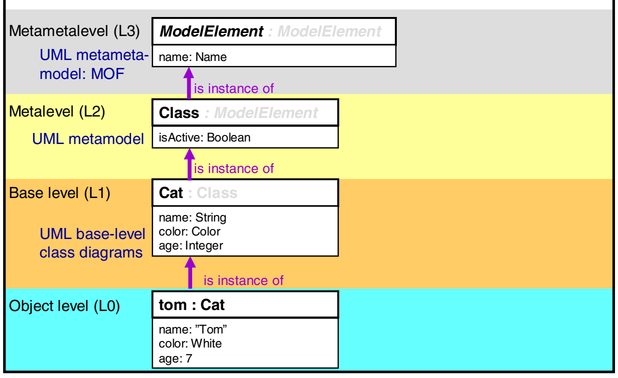
UML metametamodel: MOF ("Meta-Object Facility")

- self-describing
- subset of UML (= reification)
- for bootstrapping the UML specification

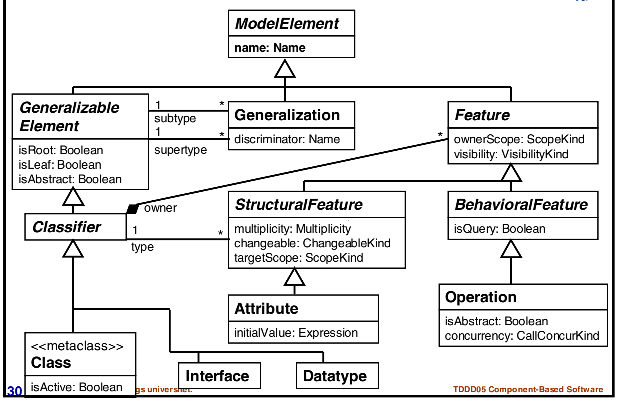
UML Extension possibility 1: Stereotypes

- e.g., <<metaclass>> is a stereotype (specialization) of a class
  - by subclassing metaclass "Class" of the UML metamodel

UML metamodel hierarchy



UML Metamodel (Simplified Excerpt)



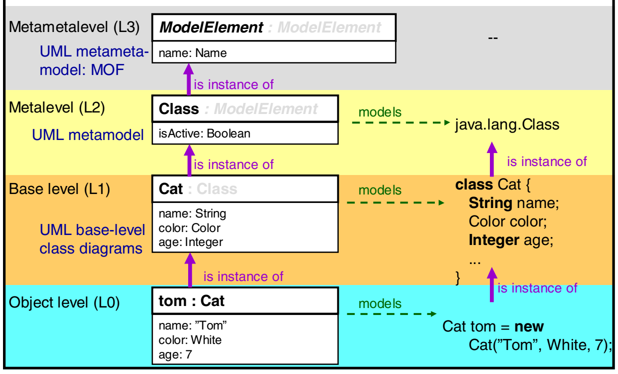
Example: Reading the UML Metamodel

Some semantics rules expressed in the UML metamodel above:

- Each model element must have a name.
- A class can be a root, leaf, or abstract
  - (inherited from GenerizableElement)
- A class can have many subclasses and many superclasses
  - (1:N relations to class "Generalization")
- A class can have many features, e.g. attributes, operations
  - (via Classifier)
- Each attribute has a type
  - (1:N relation to Classifier),

    e.g. classes, interfaces, datatypes

UML vs. programming language metamodel hierarchies



Caution

- A metamodel is **not** a model of a model
  but a model of a *modeling language* of models.
- A model (e.g. in UML) describes a language-specific software item at the *same* level of the metalevel hierarchy.
  - In contrast, metadata describes it from the next higher level, from which it can be instantiated.
- MOF is a subset of UML able to describe itself
  – no higher metalevels required for UML.

4. Component Markup

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

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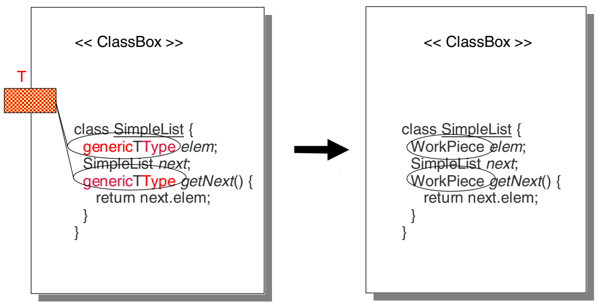
Markup Languages

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

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 from naming conventions

Generic Types in COMPOST



Java Beans Naming Schemes

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

Markup by Comments

- Javadoc tags, XDoclet
  - @author
  - @date
  - @deprecated
- Java 1.5 attributes
  - Can annotate any declaration e.g. class, method, interface, field, enum, parameter, ...
  - predefined and user-defined
  - **class** C **extends** B {
    @Overrides
    public int foo() { ... }
    ...
    }
- C# attributes
  - //@author
  - //@date
  - //selfDefinedData
- C# /.NET attributes
  - [author(Uwe Assmann)]
  - [date Feb 24]
  - [selfDefinedData(...)]

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!

What Have We Learned? (1)

- *Reflection* is a program's ability to reason about and possibly modify itself or other programs with the help of metadata.
  - Reflection is enabled by *reification* of the metamodel.
  - *Introspection* is thinking about a program, but not modifying.
- A metaprogram is a program that computes about programs
  - Metaprograms can execute at the base level or at the metalevel.
  - Metacode can execute statically or at run time.
    - 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

What Have We Learned? (2)

- The UML metamodel is a description of UML specified in terms of the UML metametamodel, MOF
  - UML models describe program objects on the same level of the meta-hierarchy level.
- Component and composition systems are reflective architectures
  - Markup marks the variation and extension points of components
    - e.g., using Hungarian notation, Comments/Annotations, external markup (separate files referencing the contents)
  - Composition introspects the markup
  - Look up type information, interface information, property information
  - or full reflection