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Unifying Views of UML[1](#_bookmark8)

# Zhiming Liu, He Jifeng and Jing Liu

*International Institute for Software Technology The United Nations University, Macao SAR China*

# Xiaoshan Li

*Faculty of Software Engineering, University of Macao, Macao SAR China*

Abstract

We present an approach to embedding a formal method into Rational Unified Process (RUP). The purposes are: (a) to unify different views of UML, (b) to enhance UML with the formal method to improve the quality of software systems; and (c) to support effective use of the formal method for system specification and reasoning with the iterative and incremental approach by providing a unified conceptual framework. One of the main features of RUP is that it is use-case driven and supports iterative development more explicit than other process models, such as the waterfall model. Object-orientation also supports better and more explicitly incremental programming than the traditional imperative programming. These together will help to scale up the use of the formal method in software system development. The model is based on Hoare and He’s Unifying Theories of Programming (UTP).

*Keywords:* Object-Orientation, RUP, UML, UTP

# Introduction

Nowadays, a software system, such as one used for health care, social security, or defence, is a model (of part) of the real world represented in a program-

1 Email: [lzm@iist.unu.edu,hjf@iist.unu.edu,xsl@umac.mo](mailto:lzm@iist.unu.edu).

Z. Liu is on leave from Department of Computer Science of the University of Leicester, England;

J. He is on leave from East China Normal University, Shanghai, China.

J. Liu is on leave from Shanghai University, China.

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ming language. As the real world keeps changing, the software system that represents it needs to be continuously maintained and evolved. To develop and maintain such an evolving software system is obviously difficult. A well disciplined process and a good modelling notation are essential to control the activities in constructing and documenting the different models obtained at different stages of the software development. The Rational Unified Process (RUP) [[32](#_bookmark47)] has emerged as a popular software development process [[33](#_bookmark48),[38](#_bookmark52),[31](#_bookmark46)]. As the modelling notation, RUP uses UML [[9](#_bookmark24)], which is the de-facto stan- dard modelling language for the development of software in a broad range of application.

RUP promotes several best practices, but one standing above the others is the idea of *use-case driven and iterative development*. In the use-case driven and iterative approach of RUP, a system development is organized as a series of short, fixed-length mini-projects called *iterations*, each for a small number of use cases. Each iteration includes its own requirements analysis, design, implementation, and testing/verification activities, described in the following subsection.

Although RUP and UML are practically popular, they are not well-founded with a formal method making it hard to analyze consistency of UML speci- fications. This work is towards an integration of a formal method with RUP and UML.

Section [2](#_bookmark0) briefly discusses the activities and UML models in RUP. We provide a summary of the main ideas of our approach in Section [3](#_bookmark2). Section [4](#_bookmark3) introduces an object-oriented notation that will be used in the proposed formal method. Section [5](#_bookmark6) shows the use of the specification notation in the specifi- cation of UML models. Instead of going into details of the formalization of UML, we will use a library system as an example to illustrate the treatment of models created in different cycles of the RUP. Finally, Section [6](#_bookmark13) concludes the paper with a discussion. The discussion on the relationship to existing work is given in Section [7](#_bookmark14).

# RUP and UML

As said earlier, each RUP iteration includes its own requirements analysis, design, implementation, testing and verification activities.

* 1. *Requirement analysis*

The requirements analysis of an iteration is to create a UML *model for the requirements* that contains an *use-case model* and a *conceptual class model*.

**Design**

**Requirement**

|  |
| --- |
| Member |
| ... |
| m5 |

Fig. 1. Iterative software development Process



**Use−case Model**

**Implementation**

Copy

~~...~~

m4

**Design Model**

... ...

Pub

Lib

LS

~~...~~

m1

:LS :Pub

:Lib :Copy

LS Lib Pub

~~...~~  ... ...

m1 m2 m3

Copy

~~...~~

**Design Model** m4

:LS :Pub

:Lib :Copy

**Implementation**

m3

m2

:Lib

:Member

:RMH

**Use−case Model**

**Conceptual Model**

Lib 1 \*Pub 1 \*Copy

... ... ...

1

\*

Member

...

... ... ...

**Conceptual Model**

Lib 1 \*Pub 1 \*Copy

**Implement**

The use-case model consists of an use-case diagram and a textual descrip- tion of each use case. The use-case diagram provides only static information about the use cases. The functional and behavioral properties described in a textual descriptions of the use cases are *partially* represented as sequences of interactions between *actors* of the use case and the system. A UML *system sequence diagram* is used to describe the possible order of the interactions be- tween the actors of a use case and the system treated as a black box, but it does not describe the change of the system state caused by such an interaction. It is important to note that a system sequence diagram does not and should not provide information about interactions among objects inside the system [[14](#_bookmark29),[38](#_bookmark52),[40](#_bookmark55)], as the these internal interactions are the concern of the design. A formalization of an use-case model should deal with both the order of the interactions (i.e. the *interactive view*) and the state changes caused by these interactions *i.e. the functional and behavioral view*. The Object Constraint Language (OCL) [[53](#_bookmark68)], as a part of UML, can describe some functional aspects, such as pre- and post-conditions of operations. However, OCL does not have

a formal semantics and it is not expressive enough to describe many useful aspects of object-orientation, such as recursive method call, dynamic binding. In this paper, we will define an object-oriented specification language (OOL) that can be used to specify functional behaviour at different levels of abstract. The conceptual model is a class diagram consisting of *classes* (also called *concepts*), and *associations* between classes. A class represents a set of *concep- tual objects* and an association determines how the objects in the associated classes are related in the *application domain*. The reason why we call the class diagram conceptual at this level is that it is not concerned with what an object does, how it behaves, or how an attribute is represented. The decisions on these issues will be made during the design phase when the *responsibilities*

of a use case are decomposed and assigned to appropriate objects.

The UML community say that the class model represents the *static view*, whereas the use-case model represents the *dynamic and interactive view* of the requirements.

* 1. *Design*

The design is to transform the model of the requirements to a *model of design* that consists of a *design class diagram* and a family of *interaction diagrams*. The interaction diagrams, representing the *interactive view* of the design, show how objects of the system interact and collaborate with each other. The cre- ation of the interaction diagrams mainly involves assignment of responsibilities to objects so that their interactions correctly realize the use cases. Use case decomposition and responsibility assignment are carried out according to the *knowledge* that the objects maintain. *What an object can do depends on what it knows, though an object does not have to do all what it can do*. What an object knows is determined by its attributes and associations with other objects.

After the responsibilities of the objects are decided, the directions of the associations (i.e. *navigation* and *visibility* from one object to another) and the methods of the classes can be determined. This will lead to the construction of the design class diagram, which shows the *static view* of the design, i.e. how the concepts and associations of the conceptual class diagram are realized by *software classes*.

* 1. *Implementation*

The implementation is to code the design in a programming language. In an object-oriented programming language, this is to define the software classes from the classes in the design class diagram and their methods based on the

interaction diagrams. Once the interaction diagrams and the design class diagram are obtained, code can be easily produced from it. It is possible to develop a tool to help in transforming a design into a code of implementation.

* 1. *Iterative and incremental model construction*

The iterative lifecycle in RUP is based on the successive enlargement and refinement of a system through multiple iterations, with cyclic feedback and adaption as core drivers to converge upon a suitable system. The system grows incrementally over time, iteration by iteration, and thus this approach is also known as *iterative and incremental*(see Figure [1](#_bookmark1)). Early iterative process ideas were known as spiral development and evolutionary development [[7](#_bookmark22)]. However, what is new in RUP is its nature of being use-case driven and its explicit support to object-orientation and incremental development.

Each cycle may consider one or a number of use cases to analyze, and build a conceptual model for them. Then these use cases can be designed to create the interaction diagrams and the design class diagram. The design is then verified, coded and tested. This one cycle can also be done again in an iterative way by taking the use cases or “parts” of a use case in turns. In the next cycle, we may take a refined or extended version of a use case from the previous cycle and refine or extend the system, or we take some new uses case to analyze, design and implement. Therefore, the models created in the new iteration are refinement and enlargement of those obtained in the previous iteration. This is shown in Figure [1](#_bookmark1).

In each iteration, the relationship between a use-case model and a con- ceptual model is that the conceptual model specifies the environment, i.e. *the state space*, under which the use cases are to be carried out. A *state* is an *object diagram* that consists of a set of objects and a set of *links* among these objects. A conceptual model is consistent with a use-case model if it is *adequate* to re- alize the functional services required by the use-case model. This consistency needs to be checked in each cycle. The design specification is required to be verified against the requirement specification of the same iteration. And the consistency and correctness need to be preserved in the following cycles. The main aim of the integration of the formal method into RUP is to allow these checks to be carried out precisely.

# Summary of the Approach

In this paper, we will focus on the incremental and iterative feature of RUP and address the following problems:

1. How to formalize a UML model of the requirements in an iteration and ensure the consistency between static and dynamic views of the model?
2. How to formalize a UML model of the design of an iteration and ensure the consistency between its static and dynamic/interaction views?
3. How to formally relate the UML models of the design and the require- ments of an iteration?
4. How to preserve the established consistency and correctness in sequent iterations?

We approach these problems by first developing a formal framework for object- oriented programming. The framework includes an object-oriented specifica- tion language (OOL) and a calculus for refinement of object-oriented designs (COOL). The calculus is relational and predicative and it is based on Hoare and He’s Unifying Theories of Programming (UTP) [[29](#_bookmark44)]. We will then study how UML models of requirements and designs can be formally represented and reasoned about in the design calculus.

When formalizing a UML model *RM* = (*cm, um*) of requirements, we de- scribe the static view *cm* as a *declaration section cdeclscm* and the use-case model *um* by a program command specification *cum*. Therefore, *RM* is defined as an object-oriented program specification *cdeclscm* • *cum*. The semantics of *cdeclscm*, *cum* and their composition • are given in the semantics of OOL. This formalization captures both the syntax and semantics of *cm* and *um* and the consistency between them. The command *cum* specifies what operations on the system states are to be carried out and in what possible order. A system state is in fact an *object diagram* of the class diagram *cm*. As one cannot decide the order in which the use cases are to be performed, OOL will allow the specification of non-determinism. Therefore, OOL will not only formalize some UML models, but also complement UML to provide functional descrip- tions of use cases. Properties of the specification, such as class invariants and constraints on associations between classes can be reasoned in the logic. Con- sistency changes in the class and use case models can be ensured by preserving these properties and even by refinement.

Similarly, for a UML model of design *DM* = (*dc, sd*) consisting of a design class diagram *dc* and a family *sd* of sequence diagrams, we formalize the design class diagram *dc* with a declaration section *cdeclsdc* in OOL. Classes in this declaration section now have methods and a method of a class may call meth- ods of other classes. Therefore, the specification of these methods describes the object interactions in the sequence diagrams. However, methods are still to be activated by commands in the main program *csd*. Therefore, a UML model of design (*dc, sd*) is also specified as the composition of a declaration

section and a main program (which again does not have a UML counterpart): *cdeclsdc* • *csd*. The consistency between the class diagram *dc* and the object sequence diagrams *sd* are captured by the semantics of *cdeclsdc* and the se- mantics of method calls in the OOL. In fact, the specification of the methods in the design class diagram combine both of *functional view* which has not UML counterpart, *behavioural view* which is described by object UML state diagrams and *interactive view* which is captured by UML object interaction diagrams. The *correctness* of the design model (*dc, sd*) *w.r.t* the requirements model (*cm, um*) is defined by the *reﬁnement* relation

*cdeclscm* • *cum* ± *cdeclsdc* • *csd*

Refinement can also be used to justify steps of incremental design (e.g. those informally used in [[33](#_bookmark48),[38](#_bookmark52)]), such as adding attributes, promoting attributes from a subclass to it superclass, encapsulating attributes, delegating function- ality of an object to its associated objects, etc. Such an integration of the refinement calculus with RUP makes the use of the design calculus more ef- fective in an iterative and incremental manner so that only a small model will be treated at each stage of an iteration.

# The Formal Object-Oriented Specification Language

We develop an object-oriented language with classes, references, visibility, dynamic binding, nested declaration, and mutual recursive method calls. Class declarations as well as commands will be defined as *designs*, the notion that is defined in [[29](#_bookmark44)].

* 1. *Syntax*

A program is of the form *cdecls* • *P* , where *cdecls* is the *declaration section*, and *P* is a command, that can be understood as the main method of a Java program.

The main method command corresponds to an active class. In this paper, we only deal with sequential programs thus we do not deal with active class in general. Therefore, in this case, the statechart of an object will start from a state when a method is invoked and then state changes will follow according to the method definition. In a multi-thread computation, we would have more than one “main method” or “run” method, so more than one active classes.

* + 1. *Class declarations*

We assume a set *CName* of *class names*. A *declaration section cdecls* is of the form *cdecls* ::= *cdecl* | *cdecls*; *cdecl*, where *cdecl* is a *class declaration* of

the following form

Class *N* extends *M* {

private *U u* = *a,* protected *V v* = *b,* public *W w* = *d*;

method *m*1(*T* 11 *x*1*, T* 12 *y*1 *, T* 13 *z*1){*c*1 }; ··· ; *mÆ*(*T Æ*1 *xÆ, T Æ*2 *yÆ, T Æ*3 *zÆ*){*cÆ*}

}

where

* *N* and *M* are names of classes in *CName*, and *M* is called the direct superclass of *N* , and the extends part is optional.
* The private declaration declares the private attributes *u* of the class, their types *U* and initial values *a*, and similarly, the protected and public dec- larations for the protected and public attributes with the meaning in Java. We define

*def*

pri(*N* ) = {*U a* = *u* | *U a* = *u* ∈ *U u* = *a*}

and similarly pro(*N* ) and pub(*N* ). We use attr(*N* ) to denote the union of these three sets of attributes; and for an attribute *u* of *N* , we use dcltype(*N.u*) to denote the type of *a* and Init(*N.u*) the initial value of *u* declared in *N* .

* The method declaration declares the methods, their value parameters *T i*1 *xi*, result parameters *T i*2 *yi*, value-result parameters *T i*3 *zi* and bod- ies *ci*, denoted by val(*N.mi*), res(*N.mi*), valres(*N.mi*), and body(*N.mi*),

respectively. We will also simply use *m*(*paras*){*c*} to denote a method dec- laration.

We will use the Java convention to write a class specification, and assume an attribute protected when it is not tagged with private or public.

* + 1. *Commands*

Our language supports typical object-oriented programming constructs:

*c* ::= *skip* | *chaos* | *c*; *c* termination, abort, sequence

| var *T* x=e | end *x* local variable declaration and undeclaration

| *c* ¢ *b* ¢ *c* | *c* H *c* conditional and nondeterministic choice

| *b* ∗ *c* | *read*(*T x*) iteration and read in a value

| *C.new*(*x*) object creation

| *le* := *e* | *le.m*(*e, v, u*) assignment and method call

where *b* is a Boolean expression, *e* an expression, and *le* an expression which may appear on the left hand side of an assignment and is of the form *le* := *x*|*le.a*|*self* where *x* a simple variable and *a* is an attribute of an object.

* + 1. *Expressions*

Expressions, which can appear on the right hand sides of assignments, are constructed according to the rules below.

*e* ::= *x*|*null*|*self* |*e.a*|*f* (*e*)

where *null* represents the special object of the special class *Null*. Notice that expressions can appear as arguments of method calls, but we do not allow method call to be an expression as we explicitly use result and val-result parameters in methods. We can include more expression such as type casting (*C*)*e* and type test (*e* is *C*), but they are not needed in this paper.

* 1. *Semantics*

In UTP [[29](#_bookmark44)], a program or a program command is identified as a *design*, which is represented by a pair (*α, P* ), where

* *α* denotes the set of variables of the program.
* *P* is a predicate of the form

*p*(*x*) ▶

' *def*

∧ *p*(*x*)) ⇒ (*ok*' ∧ *R*(*x, x*'))

*R*(*x, x* ) = (*ok*

where *x* and *x*' stand for the initial and final values of program variables *x* ⊆ *α*, the predicate *p*, called the *precondition* of the program, characterizes the initial states in which the activation of the program will lead its execution to termination, and the predicate *R*, called the *post-condition* of the program, relates the initial states of the program to its final states. We describe the termination behaviour of a program by the Boolean variables *ok* and *ok*', where the former is true if the program is properly activated and the later becomes true if the execution of the program terminates successfully.

A program command usually modifies a subset of the program variables *α*. Let *V* be a subset of *α* , the notation *V* : (*p* ▶ *R*) denotes the (*framed*) design

*p* ▶ (*R* ∧ *w*' = *w*)

where *w* contains all the variables in *α* but those in *V* . *V* is called the frame of the design *p* ▶ *R*. In the examples, we often omit the frame of a design by assuming that a design only changes the value of a variable *x* if its primed version *x*' occurs in the design.

A design *D*2

*def*

= (*α, P*2) is called a *reﬁnement* of *D*1

*def*

= (*α, P*1), denoted

*D*1 ± *D*2, if *P*2 entails *P*1, i.e.

∀*x, x*'*,..., z,z*' · (*P*2 ⇒ *P*1 )

where we assume that *α* contains *x,... , z*.

Let *ρ* be a mapping from *α*2 to *α*1 that can be defined as a design too, then

*def*

a design *D*2 = (*α*2*, P*2) is a *reﬁnement under the mapping* of *D*1 = (*α*1*, P*1)

under mapping *ρ* if

∀*x* ∈ *α ,* ∀*y*' ∈ *α*' · ((*ρ*; *P* ) ⇐ (*P* ; *ρ*))

2 1 1 2

where *α*'

1

is the set of primed versions of those variables in *α*1; and the seman-

tics of sequential composition is formally defined later.

We will follow this classical way of defining a state-based model for a programming language and define our OOL in terms of variables, states, ex- pressions, commands, declarations and programs. However, for simplicity, the above model adopts a universal data type and allows neither reference types nor nested declarations. To formalize the behaviour of an object-oriented program, we have to take into account the following features:

* A program operates not only on variables of primitive types, such as inte- gers, but also objects of reference types.
* To protect attributes from illegal accesses, the model has to address the problem of visibility of attributes to the environment.
* An object can be associated with any subclass of its originally declared one. To validate expressions and commands in a dynamic binding environment, the model must keep track of the current type of each object.
  + 1. *Values and objects*

A value is either a member of a primitive type or an *object identity*. We assume an infinite set *REF* of object identities that can be referred to, and *null* ∈ *REF* . An *object o* is an entity defined by the following structure

*o* ::= *null*| *< ref,* type*,* state *>*

where *ref* ∈ *REF* , and type is a class name, and state is a mapping from attr(type) to objects. For an object *o* =*< ref, C,σ >*, we use *identity*(*o*) to denote the identity *ref* of *o*, type(*o*) to denote the type name *C* of the object *o*, state(*o*)(*a*) to denote the value *σ*(*a*) of an attribute *a* of class *C*. When there is no confusion, we also use *C* to denote the set of objects *o* such that type(*o*)= *C*, and in this case *C* also denotes the *semantic class/type* and we can say *o* ∈ *C*.

Let O be the set of all objects, including *null*, such that for any *o*1 and *o*2 in O, *identity*(*o*1) = *identity*(*o*2) implies type(*o*1) = type(*o*2) and state(*o*1)= state(*o*2). We therefore can use identity of an object in O to re- fer to the object. In the rest of the paper, an object *o* =*< ref, C,σ >* means one in O if there is no confusion, and will use *ref.a* to denote state(*o*)(*a*), and type(*ref* ) to denote type(*o*).

Notations: We introduce the following notations:

* A class *N* is said to be a subclass of *M* , denoted by *N* ≤ *M* , if *N* = *Null*

or *N* = *M* , or there exists a finite set {*Ci* | 0 ≤ *i* ≤ *n*} of classes such that

*N* = *C*0*, M* = *Cn and* super(*Ci*)= *Ci*+1*,* for 0 ≤ *i < n*

* Let *s* =*< s*1*,... , sk >* be a non-empty sequence. We use *head*(*s*) to denote

*def*

the first element *s*1of *s*; *tail*(*s*) = *< s*2*,... , sk >* that is the sequence ob-

tained from *s* by removing its first element (it can be the empty list *< >*);

|*s*| the length *k* of *s*; and *πi*(*s*) the *ith* element *si*, for *i* ∈ {1*,... , k*}.

* Let *S* and *S*1 be sets. For better reading in the context of semantic defini- tion, we define *S*1 Œ *S* to be the set with the elements of *S*1 being removed from *S*.
* For a mapping *F* : *D* '−→ *E*, *d* ∈ *D* and *r* ∈ *E*

*def*

'

*F* ⊕ {*d* '→ *r*}

' ∧ ∀*b* ∈ {*d*} Œ *D* • *F* '(*b*)= *F* (*b*)

= *F , where F* (*d*)= *r*

* For an object *o* =*< ref, C,σ >*, an attribute *a* of *C* and an entity *d* which is either a member of a primitive type or an object in O,

*def*

*ref* ⊕ {*a* '→ *d*} = *< ref, C,σ* ⊕ {*a* '→ *d*} *>*

* For a set *S* ⊆ O of objects,

*def*

Œ

*S* {*< ref, C, σ >*} = {*o* | *identity*(*o*)= *ref* } *S* ∪ {*< ref, C,σ >*}

*def*

*Ref* (*S*) = {*ref* | *ref* is the identity of an object in *S*}

* + 1. *Variables and states*

Our model describes the behaviour of an object-oriented program by a design containing the following logical variables as its *free variables*.

* + - 1. cn: its value is the set of class names which are declared so far, and it is modified by a class declaration.
      2. Each class *N* ∈ cn is associated with
         1. attr(*N* ): the set of class *N* ’s (declared or inherited) attributes. We also use *a* ∈ attr(*N* ) to denote that *a* is an attribute name of class *N* .
         2. op(*N* ): the set of class *N* ’s (declared and inherited) methods.

{*m*1 '→ (*paras*1*, D*1 )*,* ·· · *, mk* '→ (*parask, Dk*)}

which states that each method *mi* has *parasi* as its formal parameters, and that the behaviour of *mi* is defined by the design *Di* referred by Def(*N.mi*). These variables are modified by class declarations.

* + - 1. For each *N* ∈ cn, Σ(*N* ) is the set of objects of class *N* current existing in the execution of the program, and it will be changed by creating a new object (and destroying an existing object that we do not deal with in this

paper). Let

*def*

Σ =

*N*[∈cn

Σ(*N* )

* + - 1. super: the partial function mapping a class to its *direct* superclass. This variable is also modified by a class declaration.
      2. var: its value is the set of variables which are known to the program. Since our language allows nested declaration, var associates each variable with a sequence of types

{(*x*1 *,< T*11 *,..., T*1*m >*)*,* ·· · *,* (*xn,< Tn*1 *,..., Tnk >*)}

where *Ti*1, for *i* ∈ {1*,... , n*}, is the most recently declared type of *xi* and denoted by dcltype(*xi*). We will also use var(*x*) to denote the sequence of types associated with *x*.

* + - 1. visattr: its value is the set of attributes which are visible from inside the current class, i.e. all its declared attributes plus the protected attributes of its superclasses and all public attributes. This value will be modified by the whole declaration of the program and by variable redeclarations.
      2. *x*: this logical variable represents the state of variable *x*. Since a variable can be redeclared, its state is usually a nonempty finite sequence of values, whose first (head) element represents the current value of variable *x*. A variable of a primitive data type can take any member of that type as its value. However, an object variable can store an object *name* or *identity* as its value.
    1. *Evaluation of expressions*

The evaluation of an expression *e* determines its type type(*e*) and its value. The evaluation makes use of the state of Σ(*C*) for each class *C* ∈ cn.

* A variable *x* is well-defined if it is declared in var, its type is either primitive and then its current value is a member of this type, or a class in cn and in this case its current value is an identity of an object.

*def*

D(*x*)

= *x* ∈ var ∧ (dcltype(*x*) is primitive ∨ dcltype(*x*) ∈ cn)

∧ dcltype(*x*) is primitive ⇒ *head*(*x*) ∈ dcltype(*x*)

∧ dcltype(*x*) ∈ cn ⇒ *head*(*x*) ∈ *Ref* (Σ(dcltype(*x*))

type(*x*) *def* ( dcltype(*x*) if dcltype(*x*) is primitive

=

type(*head*(*x*)) otherwise

*def *

value(*x*) = *head*(*x*)

* The *null* object expression,

*def*

*def*

*def*

D(*null*) = *true,* type(*null*) = *NU LL,* value(*null*) = *null*

* *self* is a special variable whose type has to be a class in cn, and it is

evaluated in the same way as other variables,

*def*

Ð(*self* )

type(*self* )

value(*self* )

= *self* ∈ var Λ dcltype(*self* ) ∈ cn

Λ *head*(*self*) ∈ *Ref* (Σ(dcltype(*self* )))

*def*

= type(*head*(*self*))

*def*

= *head*(*self*)

* An attribute *le.a* is defined only when *le* is of type of a class and attached to an non-null object, and *a* is an attribute name. An attribute is thus defined inductively as follows:

*def*

Ð(*x.a*)

= Ð(*x*) Λ dcltype(*x*) ∈ cn Λ *head*(*x*) /= *null*

Λ type(*x*)*.a* ∈ visattr

type(*x.a*) value(*x.a*)

*def*

= type(*head*(*x*)*.a*)

*def*

= *head*(*x*)*.a*

D(*le.a*) value(*le.a*) type(*le.a*)

*def*

= D(*le*) Λ type(*le*)*.a* ∈ visattr

*def*

= vaule(*le*)*.a*

*def*

= type(value(*le*)*.a*)

* The following exemplifies the well-definedness and evaluation of built-in expressions

Ð(*e/f* )

*def*

= Ð(*e*) Λ Ð(*f* ) Λ type(*e*)= *Real*

Λ type(*f* )= *Real* Λ value(*f* ) /=0

value(*e/f* )

*def*

= value(*e*)*/*value(*f* )

The semantics of the equality *e*1 = *e*2 is the *reference equality*:

Ð(*e*1) Λ Ð(*e*2 ) Λ (value(*e*1)= value(*e*2 )) Λ (type(*e*1)= type(*e*2))

* + 1. *Semantics of commands*

A typical aspect of an execution of an object-oriented program is about how objects are to be attached to program variables (or entities [[43](#_bookmark57)]). An at- tachment is made by an assignment, the creation of an object or passing a parameter in a method invocation.

When we define the semantics **[**E **]** of an element E of the language, we will use E itself to denote its semantics in a semantic defining equation.

Command *skip* terminates and does not change the state

*def*

*skip* = $ : (*true* ▶ *true*)

Command *chaos* has the weakest specification

*def*

*chaos* = $ : (*false* ▶ *true*)

Assignments: There are two cases of assignments. The first is to (re-)attach a value to a variable. This can be done only when the type of the object is consistent with the declared type of the variable. The attachment of values

to other variables are not changed.

*def*

*x* := *e* =

{*x*} : Ð(*x*) Λ Ð(*e*) Λ (type(*e*) ≤ dcltype(*x*)) ▶ (*x*' =*<* value(*e*) *>* ·*tail*(*x*))

The second case is to modify the value of an attribute of an object attached to a variable. This is done by finding the attached object in the system state Σ and modify its state accordingly. Thus, all variables that points to the identity of this object will be changed.

*def*

*le.a* := *e* = {Σ(type(*le*))} : (Ð(*le.a*) Λ Ð(*e*) Λ (type(*e*) ≤ dcltype(*le.a*))) ▶

(Σ(type(*le*))' = Σ(type(*le*)) {value(*le*) ⊕ {*a* '→ value(*e*)})

Condition choice: is defined in the traditional way:

*P* ¢ *b* ¢ *Q*

We use

*def*

= (Ð(*b*) Λ type(*b*)= *Bool*)

⇒ (*P* Λ value(*b*) ∨ *Q* Λ ¬value(*b*))

if{(*bi* −→ *ci*)|1 ≤ *i* ≤ *n*}fi

to denote the multiple choice statement. Its semantics is defined to be the design

*n n*

^(Ð(*bi*) Λ type(*bi*)= *Bool*) ⇒ \_(value(*bi*) Λ *ci*)

*i*=1

*i*=1

Non-deterministic choice is defined as

*def*

*P* H *Q* = *P* ∨ *Q*

Sequential composition corresponds to relational composition:

' ' *def* '

*P* (*s, s* ); *Q*(*s, s* ) = ∃*m* · *P* (*s, m*) Λ *Q*(*m, s* )

Loop statement is defined in terms of the weakest fixed point:

*b* ∗ *P*

*def*

= *µX.*(*P* ; *X*) *b skip*

¢ ¢

Object creation: The execution of *C.New*(*x*) (re-)declares variable *x*, creates a new object, attaches the object to *x* and attaches the initial values of the attributes to the attributes of *x* too.

*def*

*C.New*(*x*) = {var*, x,* Σ(*C*)} : *C* ∈ cn ▶ ∃*ref* /∈ *Ref* (Σ)•

0 Σ(*C*)' = Σ(*C*) ∪ {*< ref, C,* {*a* '→ Init(*C.a*) | *a* ∈ attr(*C*)} *>*}Λ 1

B (*x* ∈ var Λ (*x* =*< ref >* ·*x*))Λ

'

(var' = {*x*} Œ var ∪ {(*x, < C >* ·var(*x*))})∨

B@

(*x* /∈ var Λ (*x*' =*< ref >*) Λ (var' = var ∪ {(*x, < C >*)}))

CCA

We use *C.New*(*x*)[*c*] to denote the command *C.New*(*x*); *x.a* := *c*, where *a* is the lists of attributes of *C*, and *c* is a list of expressions of the same length.

Variable declaration: declares a variable and initializes it:

*def*

var *T x* = *e* = {*x,* var} : Ð(*e*) Λ (type(*e*) ≤ *T* ) ▶

0

1

((*x* ∈ var Λ *x*' =*<* value(*e*) *>* ·*x*Λ

B@

C

var' = {*x*} Œ var ∪ {*< T >* ·var(*x*)}∨

A

*x* /∈ var Λ (*x*' =*<* value(*e*) *>*) Λ (var' = var ∪ {(*x, < T >*)})

Variable undeclaration: terminates the block of the permitted use of a variable:

*def*

x

end *x* = {var*, x*} : ( ∈ var) ▶

!

(|var(*x*)| =1 Λ var' = {*x*} Œ var)∨

(|var(*x*)| *>* 1 Λ *x*' = *tail*(*x*) Λ var' = {*x*} Œ ∪{(*x, tail*(var(*x*)))})

Read in Value: is defined as

*def*

*read*(*T x*) = ∃*c*0 · (var *T x* = *c*0 )

Method Call: Let *v*, *r* and *vr* be lists of expressions. The command *le.m*(*v, r, vr*) assigns the values of the actual parameters *v* and *vr* to the formal value and value-result parameters of the method *m* of the object *o* that *le* refers to, and then executes the body of *m*. After it terminates, the value of the result and value-result parameters of *m* are passed back to the actual parameters *r* and *vr*.

*def*

*le.m*(*v, r, vr*) = D(*le*) Λ type(*le*) ∈ cn Λ *m* ∈ op(type(*le*)) ⇒

!

∃*N* • (type(*le*)= *N* ) Λ var *N self* = *le, T*1 *x* = *v, T*2 *y* = *r, T*3 *z* = *vr*;

Ψ(*N.m*); *r, vr* := *y, z*; end *self, x, y,z*

where *x, y, z* are the value, result and value-result parameters of the method of class type(*le*), and Ψ(*N.m*) stands for the design associated with method *m* of class *N* , that will be defined in Section 4.2.6.

* + 1. *Semantics of a class declaration*

A class declaration *cdecl* given in Section [4.1.1](#_bookmark4) is well-defined if the following conditions hold.

* + - 1. *N* has not been declared before: *N* /∈ cn, *N* and *M* are distinct: *N* /= *M* , and the attribute names of *N* are distinct

*distinct*(*u* · *v* · *w*)

where *distinct* can be obviously defined.

* + - 1. The initial values of the attributes matches their corresponding types.

∀*i* : 1*..m* • type(*ui*)= *Ui* Λ ∀*i* : 1*..n* • type(*vi*)= *Vi*

Λ ∀*i* : 1*..k* : •type(*wi*)= *Wi*

* + - 1. The method names are distinct

*distinct*(*< m*1*,..., mÆ >*)

* + - 1. The parameters of every method are distinct.

!

∀*i* : 1*..l* • *distinct*(*xi* · *yi* · *zi*)Λ

|*xi*| = |*T i*1 |Λ |*yi*| = |*T i*2 |Λ |*zi*| = |*T i*3|

Let D(*cdecl*) denote the conjunction of the above conditions . The class dec- laration *cdecl* adds the structural information of class *N* to the state of the following up program, and this role is characterized by the following design.

*def*

*cdecl* = {cn*,* super*,* pri*,* protattr*,* pub} : Ð(*cdecl*) ▶

0

1

cn' = cn ∪ {*N* }Λ super' = super ⊕ {*N* '→ *M* }Λ

pri' = pri ⊕ {*N* '→ {*< U u* = *a >*}}Λ pro' = pro ⊕ {*N* '→ {*< V v* = *b >*}}Λ pub' = pub ⊕ {*N* '→ {*< W w* = *c >*}}Λ

B

B@

A

CC

op' = op ⊕ {*N* '→ {(*m*1 '→ (*paras*1*, c*1))*,.. .,* (*mÆ* '→ (*parasÆ, cÆ*))}}

where the dynamic behaviour of the methods cannot be defined before the dependency relation among classes is specified. At the moment, the logical variable op(*N* ) binds each method *mi* to code *ci* rather than its definition which will be calculated in the end of the declaration section.

* + 1. *Semantics of a program*

A class declaration section *cdelcs* comprises a sequence of class declarations. Its semantics is defined from the semantics of a single class declaration given in the previous subsection, and the semantics of sequential composition. How- ever, the following well-definedness conditions need to be enforced:

*D*1: All class names used in the variable, attribute and parameter declarations are defined in the section.

*D*2: The function super does not induce circularity.

*D*3: No attributes of a class can be redefined in its subclasses.

*D*4: No method of a class is allowed to redefine its signature in its subclass.

Let *cdecls* be a class declration section and *P* a command, the meaning of a program (*cdecls* • *P* ) is defined as the composition of the meaning of class declarations *cdecls* (defined in Section [4.2.5](#_bookmark5)), the design *init*, and the meaning of command *P* :

*def*

*cdecls* • *P* = (*cdecls*; *init*; *P* )

where the design *init* performs the following tasks

* + - 1. to check the well-definedness of the declaration section,
      2. to decide the values of attr and visattr from those of pri, pro and pub.
      3. to define the meaning of every method body *c*.

The design *init* is formalized as:

*def*

*init* = {visattr*,* attr*,* op} : Ð1 Λ Ð2 Λ Ð3 Λ Ð4 ▶

0 visattr' = S*N*∈cn{*N.w* | ∃*T, d*• *< T w* = *d >*∈ pub(*N* )}Λ 1

B@ CA

∀*N* ∈ cn • attr'(*N* )= ∪{pri(*N* ) ∪ pro(*M* ) ∪ pub(*M* ) | *N* ≤ *M* }Λ

op'(*N* )= {*m* '→ (*paras,* Ψ(*N.m*)) | *m* ∈ op(*M* ) Λ *N* ≤ *M* }

where the family of designs Ψ(*N.m*) defined by a set of recursive equations. It contains for each class *N* ∈ cn, each class *M* such that *N* ≤ *M* , and every method *m* ∈ op(*M* ) an equation

Ψ(*N.m*)= *FN.m*(Ψ) where supercalss(*N* )= *M*

where *F* is constructed according to the following cases.

Case (1) *m* is not defined in *N* , but in a superclass of *N* , i.e. *m* /∈ op(*N* ) ∧ *m* ∈ ∪{op(*M* ) | *N* ≤ *M* }. Then a call to the method *m* in the environment of *N* will be executed according to the definition of *m* in the *lowest* superclass of *N* that declares the method. Let *M* be that lowest superclass of *N* , i.e. *m* is declared in *M* but no subclass of *M* declares *m*. The defining equation for *FN.m*(Ψ) in this case is

*def*

*FN.m*(Ψ) = *Set*(*N* ); *φN* (body(*M.m*)); *Reset*

Case (2) *m* is a method defined in class *N* . In this case, the behaviour of the method *N.m* is captured by its body and the environment in which it is executed

*def*

*FN.m*(Ψ) = *Set*(*N* ); *φN* (body(*N.m*)); *Reset*

where the design *Set*(*N* ) finds out all attributes visible to class *N* , whereas

*Reset* does it for the main program:

*def* '

!

*Set*(*N* )

= {visattr} : *true* ▶ visattr =

{*N.a* | *a* ∈ pri(*N* )}∪ {*M.a* | *N* ≤ *M, a* ∈ pro(*M* )}∪

{*M.a* | *M* ∈ cn*,a* ∈ pub(*M* )}

*def* '

*Reset* = {visattr} : *true* ▶ visattr = {*M.a* | *M* ∈ cn*,a* ∈ pub(*M* )}

The function *φN* renames the attributes and methods of class *N* in the code

*body*(*N.m*) by adding object reference *self* :

*def*

*φN* (*skip*) = *skip*

*def*

*φN* (*chaos*) = *chaos*

*def*

*φN* (*p*1; *p*2) = *φN* (*p*1); *Set*(*N* ); *φN* (*p*2)

*def*

*φN* (*P*1 *ab d P*2 ) = *φN* (*P*1) *a φN* (*b*) *d φN* (*P*2 )

*def*

*φN* (*P*1 H *P*2 ) = *φN* (*P*1) H *φN* (*P*2)

*def*

*φN* (*b* ∗ *P* ) = *φN* (*b*) ∗ (*φN* (*P* ); *Set*(*N* ))

*def*

*φN* (var *T x* = *e*) = var *x* : *T* = *φN* (*e*)

*def*

*φN* (end *x*) = end *x*

*def*

*φN* (*C.New*(*x*)) = *C.New*(*φN* (*x*))

*def*

*φN* (*le* := *e*) = *φN* (*le*) := *φN* (*e*)

*def*

*φN* (*le.m*(*v, r, vr*)) = *φN* (*le*)*.m*(*φN* (*v*)*, φN* (*r*)*, φN* (*vr*))

*def*

*φN* (*m*(*v, r, vr*)) = *self.m*(*φN* (*v*)*, φN* (*r*)*, φN* (*vr*))

(

*def self.x* ∃*M* · *N* ≤ *M* Λ *x* ∈ attr(*M* )

*φN* (*x*) =

*x otherwise*

*def*

*φN* (*self* ) = *self*

*def*

*φN* (*le.a*) = *φN* (*le*)*.a*

*def*

*φN* (*null*) = *null*

*def*

*φN* (*f* (*e*)) = *f* (*φN* (*e*))

Notice that we did not introduce the syntax *super.m* to explicitly indicate the call to a method according to its definition in the superclass. Instead the a method call will be executed according to the definition of method at the lowest position in the inheritance hierarchy. There is no difficulty to introduce *super.m* and define its semantics accordingly.

# Specifying UML Models

This section uses an iterative development of a library system as an example to show how to specify and reason about UML models of requirements analysis and designs. We refer the reader to our paper [[40](#_bookmark55)] for details of formal speci- fication of UML models of requirements, and to [[37](#_bookmark53),[36](#_bookmark51)] for a formal semantics of UML sequence diagrams.

* 1. *Conceptual class diagram*

A class in a class diagram is specified as class declaration. An association between two classes *N* and *M* is a type of pairs of objects of *N* and *M* , and modelled as a class that has two attributes with the association’s *end roles N* and *M* as their types.

Assume that an iteration of a library system development considers the use case to record a copy and the conceptual model in left diagram of Figure [2](#_bookmark7). A library *Lib Owns* a number of *Publication*s and each publication *Contains* some *Copy*(ies).

We specify this diagram as *CM*1 below:

Class *Lib* {*String name, String address*}; Class *Copy* {*String id*}; Class *P ub* {*String id, String title, String author, String isbn*}; Class *Contains* {*P ub p, Copy c*}; Class *Owns* {*Lib lib, P ub p*}

|  |  |  |  |
| --- | --- | --- | --- |
| Lib  ~~...~~ | 1 \* Publication 1  owns ... contains  **Conceptual Model** |  | Copy  ~~...~~ |
| Librarian | RecordCopy  **Use−case Model** | | |



Lib

1

\*

1

\* Copy

~~...~~  owns

1 has

\*

Member

... contains  ~~...~~

**Conceptual Model**

RecordCopy

Librarian

RegisterM

**Use−case Model**

...

Publication

Fig. 2. Models of the Requirements for Cycle 1 (Left) and Cycle 2 (Right)

**Requirement**

**Requirement**

We also assume the set of objects Σ(*N* ) is initially empty for each class *N* , and the operations *S.f ind*(), *S.add*(), and *S.delete*() for a set *S*. For the above declared conceptual class diagram, we have

PLib *Lib* = ∅; PPublication *Publication* = ∅; PCopy *Copy* = ∅; POwns *Owns* = ∅; PContains *Contains* = ∅

* 1. *Use cases*

The informal identification and description of a use case is important for the creation of the conceptual model to support it. However, the formal specifi- cation of the use cases depends on the specification of the conceptual model. We have a *canonical form* of a use case specification by introducing a *use-case handler* class [2](#_bookmark9) . At any time during the execution, this class will only have a single instance. Considering the use case *RecordCopy* that adds a new copy of an *existing* publication to the library. We specify this use case by introducing a use case handler class *LS* (denoting the logic library system):

*CM*1 ; *//*\*\* import the conceptual model

Class *LS* ::

method *RecordCopy*(*< String cid, String pid >*){

∃*p* ∈ Σ(*P ub*)*,l* ∈ Σ(*Lib*) • *p.id* = *pid* Λ (*l, p*) ∈ Σ(*Owns*) ⇒

*Copy.New*(*c*)[*cid*]; var *P ub p* = Σ(*P ub*)*.f ind*(*pid*);

Σ(*Copy*) := Σ(*Copy*) ∪ {*c*}Λ Σ(*Contains*) := Σ(*Contains*) ∪ {*< p, c >*};

end *c, p*}

In the specification, we have used programming commands, programming con- structs, predicate and logical connectives. This is because that programming commands and constructs have been defined as predicates and logical oper- ations. Also *c*1 ∧ *c*2 does not specify the order in which of the commands *c*1

2 This is suggested by the *facade controller pattern*.

and *c*2 are executed.

Then we define the system specification by defining the main method in which

*RCopy*

*def*

= *read*(*String cid, String pid*); *hrc.RecordCopy*(*cid, pid*) in the fol-

lowing statement:

main(){var *Bool stop* = *false, Services s*; *LS.N ew*(*hrc*); *Lib.N ew*(*lib*);

¬*stop* ∗ (*read*(*s*); if {*s* = ”*RecordCopy*” −→ *RCopy*} fi; *read*(*stop*));

end *stop, s*}

where *Services* denotes the set of *names* of services that the library system provides. When further use cases are developed, their names are added to *Services* and their executions are added to the command set in the multiple choice statement of the main method.

In the case for sequential programs, only one instance *h* of a use-case handler *H-Handler* is needed and *h.op* can be simply written as *op*. Then each use case *UH* is a piece of sequential program, and whole main program main() is an iterative deterministic choice among the use cases:

¬*stop* ∗ (*read*(*service*); if {*service* = *H* −→ *UH* } fi; *read*(*stop*))

A call to a system operation *m*(*x, y, z*) can also be written as a CSP-like process, where *x*, *y* and *z* are the value, result and value-result parameters:

*m*?*x* −→ *m*(*x, y, z*); *m*!*y*

Then use case *H* as a whole can be written as a CSP process *UH* and the program *P* in the canonical system specification can be specified as an

iterative process (*UH*1

[] ··· []*UHÆ*

)∗.

Therefore our methodology is:

* For a sequential software development, after the system operations are iden- tified and specified in the use-case handler classes, writing the formal speci- fication of the use cases becomes writing a specification of the *main method P* of the object-oriented software. Although it will not affect the overall functionality of the system, it is recommendable to have a handler class for each use case as in the normal form of the system specification. This makes the method more programmatic and fit in an iterative development process better. In a later stage of the design, we can refine the specification to combine some classes.
* For a concurrent system, writing the formal specification of the use cases is to write the specification of the *run methods* of the concurrent actors that requires services from the system.

However, as suggested in UML, the development takes a sequential view first and treats concurrency in the implementation stage by using *activity*

*diagrams*. Then the design and implementation of the system is mainly to design and implement the system operations by decomposing them into interactions between objects of the system.

We have a third suggestion in our component calculus [[26](#_bookmark36)] to deal with concurrency at the level of component compositions via the interfaces and protocols of components.

This is a typical top-down development, but the use cases and system opera- tions can be taken in turns in an iterative process.

In general, a use case is more complicated than the one we discussed above and may have alternatives and *exceptional courses of events*. Due to the space limit, we cannot treat such a use case in this paper. However, use cases [[33](#_bookmark48),[38](#_bookmark52)] show that the method for informal description of such a general use case, the drawing of its system sequence diagram, and the specification of the design of the system operation identified in the sequence diagram is quite programmatic and can scale up very well. The formalization in OOL can be worked out systematically for the informal description.

*By calculating the semantics of* (*CM*1; *HandleRcopyDecl*)• main() *within our model, we can check that the conceptual class diagram is consistent with the use case speciﬁed speciﬁcation*. The semantics supports to check the well- definedness of the declaration section (*CM*1; *HandleRcopyDecl*), the well- definedness of the commands in main(). The well-definedness of (*CM*1; *Handle RcopyDecl*) implies the well-formedness of the corresponding UML class dia- gram, and the *consistency* between the class diagram and the use case model. The sufficient condition to ensure the overall consistency is that semantics of the composition

(*CM*1; *HandleRcopyDecl*) • main()

does not equal to *chaos*. An intuitive understanding about the consistency problem is to think of a static inconsistency, such as missing class or association and conflict names, as an “compiling error” of the program (*CM*1; *HandleRcopy Decl*)•main(), and a dynamic inconsistency, such as violation of pre-condition or invariants and dynamic binding error, as an “execution error” of the pro- gram. The advantage of the formalization is that it enables us to reason about inconsistency without compilation and execution and the reasoning can be done at the requirement level. Notice that within our semantic framework, a correction of any inconsistency is then formally treated as a *reﬁnement* of the program specification.

* 1. *Interaction diagrams and design class diagrams*

To specify a sequence diagram and a design class diagram, we need to refine the classes in the conceptual model into *software classes* by adding methods, and realizing the associations by attributes of classes. Roughly speaking, an



**Design**

**Design**

|  |  |
| --- | --- |
| LS | |
| RecordCopy(cid, pid) | |
| 1  1 | controls |

|  |  |
| --- | --- |
| Publication | |
| id: String title: String author: String isbn: String | |
| makeCopy(id) | |
| contains | 1  \* |
| Copy | |
| id: String | |

|  |
| --- |
| **Interaction Diagram ID1** |
| :Lib  M:Member−set  :LS <<new>>  m:Member  RegisterM() makeMember()  m:=creat()  add()  **Interaction Diagram ID2** |
| LS  RecordCopy(cid, pid, lid) RegisterM(ml)  1  controls  1  owns  1 \*  Copy id: String  Member  String: name String: title String: id  String: address **Design Class Diagram** |

Fig. 3. Models of the Designs for Cycle 1 (Left) and Cycle 2 (Right)



:Lib

Cp:Copy−set

<<new>>

Pub:Publication−set c:Copy

RecordCopy() add()

p:=find()

makeCopy()

c:=creat()

add()

Lib

1

\*

owns

**Design Class Diagram**

add(cid, pid)

name: String address: String

:LS

p:Publication

**Interaction Diagram ID1**

incoming message to a class in a sequence diagram corresponds to a method of the class, the outgoing messages of the class following that incoming message is specified as sequential composition of method calls. Formal definitions of sequences diagrams are given in our related work in [[37](#_bookmark53),[36](#_bookmark51)]. For example, the object sequence diagram and its design class diagram in Figure [3](#_bookmark10) (on the left) are specified by the following class declarations:

Class *Lib* {*String name, String address* P*P ub pub*; //\*\* newly added

method *add*(*< String cid, String pid >*){

var *P ub p* = *P ub.find*(*pid*); *p.makeCopy*(*cid*); end *p*}};

Class *P ub* {*String id, String title, String author, String isbn,* P*Copy Cp*;

method *makeCopy*(*< String cid >*) {*Copy.New*(*c*)[*cid*]; *Cp.add*(*c*)}};

Class *Copy* {*String id*};

Class *LS* {*Lib lib*;

method *RecordCopy*(*< String cid, String pid >*){*lib.add*(*cid, pid*)}}

In the design, main() method is *almost* the same as that in the use-case model.

main(){var *Bool stop* = *false, Services s*; *Lib.N ew*(*lib*); *LS.N ew*(*ls*)[*lib*];

¬*stop* ∗ (*read*(*s*); if {*s* = ”*RecordCopy*” −→ *RCopy*} fi; *read*(*stop*));

end *stop, s*}

Define the data refinement mapping:

*def*

Σ(*P ub*) = *ls.lib.P ub,* Σ(*Contains*) =

*def* [

*def*

Σ(*Copy*) =

*p*∈*ls.*[*lib.P ub*

*def*

{*p*}× *p.Cp*

*p*∈*lib.P ub*

*p.Cp,* Σ(*Owns*) = {*ls.lib*}× *ls.lib.P ub*

*With our model and reﬁnement calculus, we can check whether a design class diagram is consistent with a family of sequence diagrams, that this design* refines *the program that represents the use-case speciﬁcation*. Details about the consistency of a model of design and the link between a UML model of design to a UML of requirements are formally addressed in [[37](#_bookmark53),[36](#_bookmark51)]. The refinement involves in adding or removing attributes, methods, classes and associations; delegating methods; and refining commands. A refinement calculus for object- oriented systems is given in [[25](#_bookmark37)] in which all these “refectoring” operations on the structure of an object-oriented program are proven to be valid refinement.

An alternative but still correct design of *RecordCopy* is to redefine the

*add*() method in *Lib*,

*Lib* :: *add*(){var *Publication , p, Copy c*;

*p* := *P ub.find*(*pid*); *Copy.New*(*c*); *p.addCopy*(*c*); end *p, c*

}

and to replace *Publication* :: *makeCopy*() by

*Publication* :: *addC*(val *Copy c*){*Cp.add*(*c*)}

However, this design adds an extra *dependency* between *Lib* and *Copy*.

* 1. *Further development of the library system*

Now consider the use case to register a member that creates a member and logs it to the library. We thus have to *extend* the class diagram on the left of Figure [2](#_bookmark7) to the one on the right, that is denoted by *CM*2, by adding the following two classes.

Class *Member* {*String name, String title, String id, String address*};

Class *Has* {*Lib lib, Member m*}

Let *SList* be the type *String* × *String* × *String* × *String* and *details*

*def*

=

(*name, title, id, address*) denote the tuple of the attributes of *M ember*. We can then specify the use case to register a member, denoted by *RegisterM* , by a use-case handler *HandleRM* which has *Lib lib* as an attribute and a method *RegisterM* . However, we can also use the same use case handler class *LS* to

handle this new use case too:

*LS* :: *RegisterM* (*< SList ml >*){

¬∃*m* ∈ Σ(*Member*) • *m.details* = *ml* Λ ∃*lib* ∈ Σ(*Lib*) ⇒

*Member.New*(*m*)[*ml*]; Σ(*Member*) := Σ(*Member*) ∪ {*m*};

S

(Σ(*Has*) := Σ(*Has*) ∪ *Æ*∈Σ(*Lib*) {*< l, m >*})}

We can prove that this use case is consistent with the extended conceptual model.

We can consider *RegisterM* independently from *RecordCopy* with its own conceptual model of classes *Lib*, *M ember* and the association *Has*. We then obtain *CM*2 by merging this model with *CM*1. If different names are used for the same concept, rename one to another.

Then the main method will be enlarged by adding the service name ”*RegisterM* ” in *Service* and adding the following command to the multiple choice statement

*def*

*RegM* = *read*(*SList ml*); *hrm.RegisterM* (*ml*)

guarded by *s* = ”*RegisterM* ”

main(){var *Bool stop* = *false, Services s*; *Lib.N ew*(*lib*); *LS.N ew*(*ls*)[*lib*];

( )

¬*stop* ∗ (*read*(*s*); if *s* = ”*RecordCopy*” −→ *RCopy,* fi; *read*(*stop*)); *s* = ”*RegisterM* ” −→ *RegM*

end *stop, s*}

Following the design patterns in [[33](#_bookmark48)], we can work out the interaction diagram and the design class diagram on the right Figure [3](#_bookmark10).

*Lib* :: P*Member M* ; *//* ∗ ∗add a new attribute to *Lib*

*Lib* :: *makeMember*(*< SList ml >*){*//* ∗ ∗add a method to *Lib New Member*(*m*)[*ml*]; *M.add*(*m*); end *m*};

*LS* :: *RegisterM* (*< SList ml >*){*lib.makeMember*(*SList ml*)}

The main method is nearly the same as in the requirement specification.

We prove the design of *RegisterM* is correct by defining the data refine- ment mapping

*def def*

Σ(*Member*) = *ls.lib.M* Σ(*Has*) = {*< ls.lib, m >* | *m* ∈ *ls.lib.M* }

With *CM*2, we can specify and design use cases *SearchMember*, *SearchPub*

and *SearchCopy*.

Borrow a copy

Now let us consider the use case *BorrowCopy* that records the fact that a registered *member* has borrowed a copy from the library. We need to introduce a new concept *Loan* that records the information of a loan of a copy by a member. The *Loan* class is associated with classes *Member* and *Copy* so that

1

has

\*

1 owns \*

1 1 1

Member

Lib

Copy

Publication

Loan

1

contains

\*

takes

\*

borrows

Fig. 4. Conceptual model for *BorrowCopy*

**Design**

|  |  |
| --- | --- |
| **Interaction Diagram ID1** | LS  Record(cid, pid) RegisterM(ml) BorrowCopy(cid)  1  controls  1  Lib owns  1  name: String \*  address: String add(cid, pid)  makeMember(id) 1 \*  makeLoan(cid) includes Copy  1 id: String  has  \* 1  Member 1 borrows  String: name Loan  String: title 1 \* String: date  String: id takes String: id  String: address  takeLoan(cid) **Design Class Diagram** |
| **Interaction Diagram ID2** |
| :Lib Cp:Copy−set Lo:Loan−set  :LS <<new>>  M:Member−set m:Member :Loan  Borrow() makeLoan()  m:=find()  c:=find()  [ m = Null c= Null ] creat() takeLoan()  add()  **Interaction Diagram ID3** |

Fig. 5. Design model for cycle 3

a member *Takes* the loan which *Borrows* a copy. The conceptual model *CM*2

is extended *CM*3 in Figure [4](#_bookmark11), and specified as follows:

*def*

*CM*3 = *CM*2; //\*\*Reuse conceptual model

Class *Loan* {*String date, String id*};

Class *T akes* {*Member m, Loan loan*} Association Class Class *Borrows* {*Copy c, Loan loan*} Association Class

We specify the use case as a method of the same handler class *LS*, though we can use a new handler.

LS:: *BorrowCopy*(val *String cid, String mid*){

∃*m* ∈ *Member* • *member.id* = *mid*

Λ∃*c* ∈ *Copy* • *c.id* = *cid* Λ ¬∃*loan* ∈ *Loan*• *< loan, c >*∈ *Borrows* ⇒

var *Loan loan, Member m*;

*Loan.N ew*(*loan*) Λ *m* := *Members.find*(*mid*); *Loan*' = *Loan* ∪ {*loan*}Λ

*Borrows*' = *Borrows* ∪ {*< loan, c >*}Λ *T akes*' = *T akes* ∪ {*< m, loan >*};

end *loan, m*

}

As the second iteration, add ”*BorrowCopy*” to *Service*, and define

*def*

*BCopy* = *read*(*String cid, String mid*); *LS.BorrowCopy*(*cid, mid*)

The main program is specified as

main(){ var *Bool stop, Service s*;

*stop* := *true*; while ¬*stop* do{ *read*(*s*); *read*(*stop*)

if {*s* = ”*RecordCopy*” −→ *RCopy, s* = ”*RegisterM* ” −→ *RegisterM, s* = ”*BorrowCopy*” −→ *BCopy*} fi;

end *s, stop*}

}

The main program can be extended as before by adding the new *BorrowCopy*

service.

The same conceptual model *CM*3 supports the specification of the use cases for finding the number of *loans* for a member *MGetLoanSize* and for a copy *CGetLoanSize*.

Design use case *BorrowCopy*

We give a design by adding an attribute P*Copy Copy* and a method *makeLoan*() to class *Copy*, an attribute P*Loan Loan* and a method *takeLoan*() to class *Member*, redefine class *Loan* so that it has an attribute *Copy c*, and redefine the method *BorrowCopy*() in *LS*. We give a UML design model in Figure [5](#_bookmark12), and its specification below:

*Lib* :: P*Copy Copy* = ∅;

*Lib* :: *makeLoan*(val *String mid, String cid*){

var *Member m, Copy c*;

*m* := *Member.find*(*mid*) Λ *c* := *Copy.find*(*cid*); *m.takeLoan*(*c*) ¢ (*c* /= *null* Λ *m* /= *null*) ¢ *chaos*; end *m, c* };

*Member* :: P*Loan Loan*;

Member :: *takeLoan*(val *Copy c*){

var *Loan loan*; *loan* := *Loan.N ew*(*loan*)[*c*]; *Loan.add*(*loan*); end *loan*

};

Class *Loan* {*Date date, String id, Copy c*}; *LS* :: *BorrowC*(val *String mid, String cid*){

*lib.makeLoan*(*mid, cid*)

}

More use cases, such as *Return a Copy*, can be developed in the next iteration.

# Conclusion

Based on UTP [[29](#_bookmark44)], we have presented a model for object-oriented programs. The model is compositional, where the well-definedness of a class is deter- mined in dependence of its constituents. Incremental code changes, as what often happen in object-oriented programming, require revising only the af- fected parts of the model and not the model as a whole. The model allows us to compose the static UML view with the UML functional view of the re- quirements, and the static UML model with the UML interaction model of the design. It also supports the verification of the correctness of a design model against a requirement models.

The important nature of the integrated method is that each iteration is only concerned with a small part of the system functionality and a small model at a time. Instead of using a traditional compositional approach, we decompose the system informally according to use cases. We obtain formal models in each iteration and compose them to form a larger system step by step. We believe that this is important for scaling up the use of a formal method. A system developed this way is easy to maintain when the business rules change. For example, consider the need to impose the restriction on the use case *BorrowCopy* that a member is only allowed to take a limited number *k* of loans. We only need to add a method *NBorrow*() method in *LS*

*LS* :: *NBorrow*(val *String mid, String cid*){

Int *n* := *LoanSize*(*mid*);

*self.Borrow*(*mid, cid*) ¢ (*n < k*) ¢ (”error”)

Then we replace *Borrow* use case with *NBorrow* in the main program. This does not need to change the implementation of any other *core* classes of the system.

Because our approach supports refinement of models by introducing mod- elling elements in an incremental manner, it clearly supports the Sketch and blueprint modes of UML usage pointed out by Martin Fowler in his invited talk at *<<*UML*>>* 2003 [[19](#_bookmark34)]. Also, our formalization of UML model in a specification in a Java-like notation can be seen as a step toward third mode of usage of UML suggested by Martin Fowler as a programming language. Being able to use UML as a programming language is very important for the success of MDA [[19](#_bookmark34),[6](#_bookmark21),[42](#_bookmark58)].

# Related Work

* 1. *Models of object-oriented programs*

There is a large number of publications on models for object-oriented program- ming, e.g. [[1](#_bookmark16),[2](#_bookmark17),[8](#_bookmark23),[4](#_bookmark18),[10](#_bookmark25),[45](#_bookmark59)]. A large body of work on modelling object-oriented

programming is based on type theories or operational semantics. Our ap- proach is among those that are state-based and uses a predicate logic.

State-based formalisms have been used in conjunction with object-oriented techniques, via languages such as Object-Z [[10](#_bookmark25)] and *V DM* ++ [[15](#_bookmark30)], and meth- ods such as Syntropy [[13](#_bookmark28)] (which uses the Z notation) and Fusion [[12](#_bookmark27)] (which is related to *V DM* ). Whilst these formalisms are effective in modelling data structures as sets and relations, they are not ideal for capturing more sophis- ticated object-oriented mechanisms, such as dynamic binding and polymor- phism.

Cavalcanti and Naumann define an object-oriented programming language with subtype and polymorphism using predicate transformer [[11](#_bookmark26),[45](#_bookmark59)]. Mikha- jlova and Sekerinski [[44](#_bookmark60)] design a rich object-oriented language by using a type system and predicate transformers as well. However, neither reference types nor mutual dependency between classes is allowed in those approaches.

There are a number of recent articles on Hoare Logics for object-oriented programming (see, e.g. [[46](#_bookmark61),[52](#_bookmark67),[30](#_bookmark45),[47](#_bookmark62)]). The normal form of a program in our paper is similarly to those in [[11](#_bookmark26),[46](#_bookmark61)]. However, a class declaration (sec- tion) and a program, as well as a command, are represented as predicates called *designs* in UTP [[29](#_bookmark44)]. This provides us with a formal characterization of the contextual/structural feature of the object-oriented programs and a *structural reﬁnement relation* between object-oriented programs [[25](#_bookmark37)]. Also the refinement relation between programs is defined as implication between their designs. The proof of a refinement will be carried out in the predicate logic rather than in a Hoare logic proof system. The notion of structural re- finement supports a formal treatment of refectorings [[20](#_bookmark35)] and object-oriented designs to support iterative and incremental development. This has turned out to be essential when we use this model to formalize and compose different UML models. Another advantage of our approach is that writing a specifica- tion in the relational calculus is quite straightforward and a specification is easy to understand. Although we have not dealt with concurrency, the power of UTP for describing different features of computing, including concurrency and communication, timing, and higher-order computing [[29](#_bookmark44),[54](#_bookmark69),[50](#_bookmark65)], makes our approach ready for extension to cope with these different aspects of object- oriented programs. Alternatively, one can also use temporal logic, such as [[3](#_bookmark19)], for the specification and verification of multithreading Java-like programs. However, we would like to deal with concurrency at a higher level when we extend this model for component-based software development [[27](#_bookmark42),[26](#_bookmark36)].

* 1. *Formalizations of UML*

The research on formal support for UML modelling (e.g. [[18](#_bookmark33),[5](#_bookmark20),[17](#_bookmark32),[16](#_bookmark31),[22](#_bookmark38),[48](#_bookmark63)]) is currently very active . However, there is a large body of work in formalizing UML and providing tool support for UML focuses on models for a particular view (e.g. a class models, statecharts, and sequence diagrams), and the trans- lation of them into an existing formal formalism (e.g. Z, VDM, B, and CSP). In contrast, we concentrate on use cases and combinations of different UML models. This is the most *imprecise* part of UML and the majority of existing literature on the UML formalization often avoids them. Our methodology is directly towards improved support for requirement analysis and transition from requirements to design models in RUP. The notion of structural refine- ment enables us to transform UML models consistently. This is very impor- tant for UML-based development as these transformations allow developers to model a system at different level of abstraction. In fact the article [[18](#_bookmark33)] pointed out the need of such correctness preserving manipulation of UML models and made the initial attempt to provide some transformations. Unfortunately, it could not go far enough and only considered transformation of class diagrams to preserve state invariant. Our choice of a Java-like syntax for the specifi- cation language is a pragmatic solution to the problems of representing name spaces and (the consequences of) inheritance in a notation such as CSP.

An earlier version of the semantic model for OOL was presented in [[24](#_bookmark39)] that does not deal with references and nested local variable declaration. Based on [[24](#_bookmark39)], the notions of refinements for commands, class declarations and programs are defined in [[25](#_bookmark37)]. Our idea about combining a conceptual class model and a use-case model was initially presented in [[39](#_bookmark54)], without using a specification language. It was embedded into a use-case driven approach for requirement analysis in the paper [[34](#_bookmark49)]. These two papers evolved into a comprehensive method for UML-based requirement analysis in [[40](#_bookmark55)] with the ideas of normal form of specification. The completeness of the model for requirement analysis can be justified by the computation model presented in [[41](#_bookmark56)]. Then we estab- lished the semantic model for OOL with references and nested local variable declaration in the report [[28](#_bookmark43)]. We have recently used OOL to give a formal semantics of UML interaction diagrams in [[37](#_bookmark53),[36](#_bookmark51)]. This paper presents the formal semantics of OOL given in [[28](#_bookmark43)] and embeds it in the context of RUP and UML based software development.

In this paper, we focus on only conceptual aspects of object orientation. Most syntactical and semantic consistency conditions defined in this paper have straightforward algorithms for checking and hence support necessary au- tomated tools [[35](#_bookmark50)]. For example, the transformation of a class diagram to a declaration section is obvious and the well-defined conditions for declaration

section is clearly consistent with the well-formed conditions of UML defined in terms of OCL. Other constraints on a class model, such as *multiplicities* of an association, properties of an *aggregation association*, characterization of an *abstract class* and *associative classes*, can be specified as state invariants that need to be preserved by use case commands [[40](#_bookmark55)].

* 1. *Future work*

We are currently working on a comprehensive set of refinement laws to support both behavioural and structural refinement of object-oriented designs. Future work also includes the extension of this method to component-based software development (e.g. [[14](#_bookmark29),[51](#_bookmark66)]) so that components can be developed in parallel, and the application of this framework to formal treatment of *patterns* [[21](#_bookmark40)]. Defining an executable semantics for the modelling language in this paper and thus to provide an executable semantics for (a subset of) UML will be attractive to the MDA [[19](#_bookmark34),[6](#_bookmark21),[42](#_bookmark58)] community [3](#_bookmark15) .

In addition, tool support, e.g. in the direction of [[23](#_bookmark41)], for formal object- oriented methods is an area of considerable significance for further industrial take-up of these methods. We are also interested in studying the difference and relationship between our model and Separation Logic [[49](#_bookmark64)].

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3 A number of panellists of the Panel of “What should a good modelling language look like” at UML’03 pointed out that a modelling language should be executable in terms of having a compiler so the testing and simulation can be carried out effectively.

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