Three-Tiered Specification of Micro-Architectures

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Abstract. A three-tiered specification approach is developed to formally specify collections of collaborating objects, say micro-architectures. (i) The structural properties to be maintained in the collaboration are specified in the lowest tier. (ii) The behaviour of the object methods in the classes is specified in the middle tier. (iii) The interaction of the objects in the micro-architecture is specified in the third tier. The specification approach is based on Larch and accompanying notations and tools. The approach enables the unambiguous and complete specification of reusable collections of collaborating objects. The layered, formal approach is compared to other approaches including the mainstream UML approach.

Keywords: object-oriented design, formal methods, micro-architectures, design patterns, frameworks, interaction, UML, reuse, evolution

1 Introduction

Class vs. micro-architecture vs. framework. An object-oriented system is a collection of encapsulated objects that collaborate among themselves to achieve specified tasks. The benefits of systems designed using OO principles include the potential for reuse, incremental extension and local modification. According to [25] and others, one can distinguish several levels of reuse and adaptation. At the lowest level, one reuses or adapts methods or classes. This level is often inadequate for reuse, and it does not appropriately scope adaptation activities since methods and classes are not “islands”. They cannot be reused and adapted independently. At the highest level, one operates on entire application frameworks. This form does not account for application development with reuse of building blocks, neither does it restrict the scope of an adaptation. In fact, our target is the intermediate level of micro-architectures, that is, collections of collaborating objects. We contend that this is the appropriate level for reuse and adaptation in object-oriented design and programming (OOD & OOP).

* This research was supported, in part, by a Collaborative Research Development grant from the Natural Sciences and Engineering Research Council of Canada and Nortel, Nuns Island, Montreal, and by the Dutch Research Organisation NWO, in the project 612.014.006 “Generation of Program Transformation Systems”.

arXiv:cs/0205052v1 [cs.SE] 19 May 2002
A running example. Let us sketch an example of a micro-architecture. Our running example is the WorldClock micro-architecture dealing with interacting MasterClock and ZonalClock objects as illustrated in Figure 1. The MasterClock object is responsible for maintaining the Greenwich Meridian Time, while the ZonalClock objects display the time in their respective zones. The MasterClock object can exist independently of the ZonalClock objects, but each ZonalClock object depends on the MasterClock object to maintain its zonal time. We thus have a one-to-many relationship between master and zonal clocks. All the objects together maintain an invariant that any zonal clock displaying the time in its zone is consistent with the master clock’s time. The MasterClock object notifies its associated ZonalClock objects whenever its time is updated. When a ZonalClock object is requested to update its zonal time, it queries the MasterClock object for the current time. If the ZonalClock object observes a time change then it updates itself to make its state (i.e., the zonal time) consistent with the time maintained by the MasterClock object. Explicit polling by the dependent ZonalClock objects for new information is not intended. The identities and the number of ZonalClock objects are not known a priori. Each ZonalClock object attaches itself to a MasterClock object upon its creation.

Micro-architectures vs. design patterns. Let us clarify our use of the term “micro-architecture” with regard to the related term “design pattern” [20]. Recall our definition: micro-architectures correspond to collections of collaborating objects. In fact, we consider micro-architectures to be the building blocks of object-oriented applications, especially of frameworks for domain-specific application development. A framework or an application contains several micro-architectures. In the actual code that embodies a framework, a certain class might contribute to more than one micro-architecture. By contrast, design patterns represent abstract, that is, application-independent designs.
Especially, the operational meaning of design patterns is deliberately vague. One might say that design patterns are the most abstract micro-architectures one can think of, and hence we might consider micro-architectures as concrete instances of design patterns within frameworks. The typical micro-architecture in a framework is more concrete than a design pattern because it will usually exhibit some domain-specific behaviour. To give an example, the WorldClock micro-architecture is a concrete instance of the Observer pattern [20]. While the WorldClock micro-architecture deals with the notion of time based on corresponding operations, the more abstract Observer pattern only involves an abstract notion of state.

In need for a specification approach An informal explanation like the one given for the running example above is certainly informative for a developer who wants to reuse or to adapt a micro-architecture. However, in order to adequately deal with the complexity of design, improve productivity, and maintain acceptable levels of software quality the developer should also be provided with an unambiguous description of software components. Informal descriptions by themselves are grossly insufficient to build future software architectures, such as those being planned in strategic applications. The mainstream approach to specify designs of such architectures is to use UML [32]. One uses class diagrams to model the static structure of entities in the design, and one describes the collaborations using object collaboration diagrams. Specifications of object interfaces are given in pseudo-code. This approach does not provide a clear description of object dependencies and the inter-object behaviours that are maintained in the collaboration. Finally note that an UML-based specification is typically not formal, although there is admittedly an ongoing effort to provide a formal interpretation of certain UML notations.

Three-tiered specification of micro-architectures We contend that we need a complete and formal approach to the specification of collections of collaborating objects. We also want this approach to be simple and to allow for a seamless integration with UML visual modelling facilities. A corresponding specification approach is the prime contribution of the present paper. Different aspects of micro-architectures are covered in three tiers:

(i) the structural properties to be maintained by the collaboration;
(ii) the roles of the collaborating objects in a black-box fashion;
(iii) the interactive behaviour in terms of the operation sequences and flow of control.

In our specification approach, we use a designated notation for each tier. The fist two tiers are covered by the formal specification language Larch [22], namely Larch traits and the Larch/C++ notation. We chose Larch because Larch makes it possible to express externally observable behaviour in an implementation independent fashion which is crucial for black-box reuse. Larch/C++ provides built-in syntactic and semantic support for specifying C++ class interfaces. This allows us to link specification and programming. As for the third tier, we use a simple logic of actions in the style of Lamport’s Temporal Logic of Actions [26].

Structure of the paper The three tiers or our specification approach are presented in the three sections 2–4 accordingly. We provide the specification of the WorldClock example throughout these sections while the mainstream UML approach is considered as well. In Section 5, we report on related work regarding the specification of design structures such as micro-architectures or design patterns. In Section 6, we conclude the paper.
2 Lowest tier: Structure

The lowest of the three tiers specifies the structural aspects of the collaboration. Besides specifying the data models for the objects in the collaboration, it also specifies the states of interest of each object, and the cardinality constraints of the relationships among the collaborating objects. We use the Larch Shared Language LSL [22] for the specification of this layer. The section is structured as follows. We first recall the diagrammatic approach of UML corresponding to this layer. Then, we provide a brief description of LSL. Finally, we give a formal specification of the structural aspects of the WorldClock micro-architecture using LSL.

2.1 UML class diagrams

In Fig. 2, we show a class diagram of the WorldClock micro-architecture as used for OOD based on UML. This design could be enhanced to include object references and pseudo-code.

![Diagram](image)

Fig. 2. Participating classes in the WorldClock micro-architecture

There exists a one-to-many relationship between MasterClock and ZonalClock objects. This relationship is expressed by means of the aggregation arrow in Fig. 2. In fact, a ZonalClock object cannot exist independently, and must be attached to a MasterClock, while the converse is not true. There is a structural aspect which is not expressed in the class diagram. We require an integrity constraint on the relationship between the MasterClock object and the ZonalClock objects, that is, the ZonalClock time must be consistent with the MasterClock time in its zone. This integrity constraint corresponds to a structural aspect because it characterises the states of interest of the participating objects in the collaboration.
2.2 The Larch Shared Language

In our layered specification approach, LSL serves for the specification of structural aspects. Let us briefly recall LSL [22] as a specification language. The unit of specification in LSL is the trait. A trait contains a set of operator declarations (say, a signature), which follows the introduces keyword, and a set of equational axioms, which follows the asserts keyword. Left- and right-hand side of an equation are separated by “==”. A signature consists of operators the domains and ranges of which are represented by sorts. An equational axiom specifies the constraints on the defined operators.

The semantics of LSL traits is based on multi-sorted first-order logic with equality rather than on an initial, final or loose algebra semantics used by other specification languages [5, 14, 21, 33]. Each trait denotes a theory, i.e., a set of logic formulae without free variables, in multi-sorted first-order logic with equality. The theory contains each of the trait’s equations, the conventional axioms of first-order logic with equality, everything which follows from them and nothing else. This means that the formulae in the theory follow only from the presence of assertions in the trait—not from their absence.

LSL also provides a way of putting traits together through an includes clause. A trait that includes another trait is textually expanded to contain all operator declarations and axioms of the included trait. Boolean operators (true, false, not, \( \lor \), \( \land \), \( \rightarrow \), and \( \leftrightarrow \)) as well as some overloaded operators such as if-then-else and “=” are built into the language, that is, traits defining these operators are implicitly included in every trait.

LSL traits can be augmented with checkable redundancies in order to verify whether intended consequences actually follow from the axioms of the trait. The checkable redundancies are specified in the form of assertions that are included in the implies clause of a trait and can be verified using Larch Prover [22]. The theory of a trait can also be strengthened by adding a generated by or a partitioned by clause. The generated by clause states the operator symbols that can generate all values of a sort. The partitioned by clause provides additional equivalences between terms. It states that two terms are equal if they cannot be distinguished by any of the functions listed in the clause.

2.3 Abstract states in the WorldClock micro-architecture

We specify the abstract states of MasterClock and ZonalClock objects using LSL traits. Since both a MasterClock and a ZonalClock maintain time, we first specify the Time sort. This is followed by a specification of the Zone sort which provides the data model for ZonalClock objects. Ultimately, we specify the objects in the WorldClock micro-architecture including the relationship between them.

The Time sort The LSL specification is shown in Fig. 3. The Time trait includes the traits TotalOrder(Time) and Integer. This is shown in the includes clause. The TotalOrder trait specifies formally the total ordering of the abstract values of Time. The signature and meaning of the operator “+” comes from the Integer trait defined in the LSL trait library. Comparison of time data is defined in terms of comparison of integers (cf. “\( \leq \)”).

\(^1\) To avoid confusion, note that “=” is the built-in “equality” operator whereas “==” is used as the connective in equations. By convention, \( t == \) true is written as \( t \). Also note that “=” binds more tightly than “==”. Otherwise, the two operators are semantically equivalent.
The “tuple of” declaration specifies *Time* data as a record structure. The signature of the *Time* trait introduces the following functions:

- **currentTime**: Returns the current time.
- **toInt**: Converts the given time into an integer.
- **fromInt**: Converts the given integer to time.
- **succ**: Given a time unit, returns the next time.
- **pred**: Given a time unit, returns the previous time.
- **inc**: Given a time *t* and an integer *i*, returns *t* incremented by *i* seconds.
- **dec**: Given a time *t* and an integer *i*, returns *t* decremented by *i* seconds.
- **max**: Given two values of time, returns the maximum of the two.
- **min**: Given two values of time, returns the minimum of the two.
- **≤**: Given two values of time, tests if the first is not later than the second.
- **isValid**: Given a value of time, returns true for a valid time and false otherwise.

**The Zone data model** The LSL specification of the data model for *ZonalClock* objects is shown in Fig. 4. Since a zonal clock should also maintain a time, the *Zone* trait includes the *Time* trait. Besides the zonal time, the *it Zone* sort includes the name and offset of a zonal clock. Hence, the structure of *Zone* is a **tuple of** three fields. Here is a brief explanation of the trait’s signature:
Zone : trait

includes Integer, String, Time

Zone tuple of
  zonalName : String,
  zonalOffset : Int,
  zonalTime : Time

introduces
  update : Time, Zone → Zone
  isUpToDate : Time, Zone → Bool

asserts
∀ z : Zone, t : Time
  update(t, z).zonalName = z.zonalName
  update(t, z).zonalOffset = z.zonalOffset
  update(t, z).zonalTime = fromInt(toInt(t) + z.zonalOffset)
  isUpToDate(t, z) == z.zonalTime = fromInt(toInt(t) + z.zonalOffset)

implies
∀ z : Zone, t : Time
  isUpToDate(t, update(t, z))

---

Fig. 4. LSL specification of Zone trait

- **update**: Given a `Time` and a `Zone`, returns a `Zone` whose the zonal-time value is equal to the given `Time` incremented by the offset of the given `Zone`.
- **isUpToDate**: Given a `Time` and a `Zone`, returns true if the zonal time is up-to-date with respect to the given master time, and false otherwise.

The **WorldClock trait** The LSL specification of the objects in the WorldClock micro-architecture, and the invariant properties of the relationship between them is shown in Fig. 5. Note that this is the only trait which deals with (mutable) objects. Both ZonalClock and MasterClock objects are defined here. The other traits `Time` and `Zone` solely define the data models. Here is a brief description of the operators declared in the WorldClock trait:

- **masterOf**: Given a ZonalClock object, returns the MasterClock object to which it is attached. The ZonalClock object depends on the MasterClock object for its current zonalTime. The totality of this function specifies the constraint that a ZonalClock object cannot exist independently of the MasterClock.
- **zonalClocksOf**: Given a MasterClock object, returns the possibly empty set of attached ZonalClock objects that depend on the MasterClock.
- **isConsistent**: Given a MasterClock, a ZonalClock, and a State, returns true if the two clocks are consistently related to each other in the state, and false otherwise.

The specification of the trait relies on the `MutableObj` library trait that specifies the sort of mutable objects according to the formal LSL model for objects [34] including a corresponding notion of `State`. In the axioms, we use the binary operator “!” to extract
WorldClock : trait

includes
  MutableObj(Time, MasterClock for Obj[Time]),
  MutableObj(Zone, ZonalClock for Obj[Zone]),
  Set(ZonalClock, Set[ZonalClock])

introduces
  masterOf : ZonalClock → MasterClock
  zonalClocksOf : MasterClock → Set[ZonalClock]
  isConsistent : MasterClock, ZonalClock, State → Bool

asserts
  ∀ m : MasterClock, z : ZonalClock, st : State
  |zonalClocksOf(m)| ≥ 0
  masterOf(z) = m == z ∈ zonalClocksOf(m)
  isConsistent(m, z, st) == (masterOf(z) = m) ∧ isUpToDate(m!st, z!st)

Fig. 5. LSL specification of WorldClock trait

the value of an object from a state. The trait performs three includes. Firstly, we include “MutableObj(Time, MasterClock for Obj[Time])” to specify the sort of mutable MasterClock objects whose abstract values are specified by the Time sort. The form “MasterClock for Obj[Time]” performs a renaming so that we can use the name MasterClock for the sort of MasterClock objects instead of Obj[Time]. Secondly, we include “MutableObj(Zone, ZonalClock for Obj[Zone])” to specify the sort of mutable ZonalClock objects. Thirdly, we include “Set(ZonalClock, ...)” so that we can deal with sets of ZonalClock objects, namely the set of ZonalClocks attached to a MasterClock. The referenced library traits MutableObj and Set can be found in [30].

3 Middle tier: Roles

The middle tier in our three-tiered specification approach uses the data model defined in the lowest tier, and identifies the services required to specify the roles of the collaborating objects to specify their externally observable inter-object behaviour. The role specification for an object includes those services in the interface of the object which take part and are pertinent to the collaboration between the object and its collaborators. All the operations of an object’s role are specified using a behavioural interface specification language (BISL). In the present paper, we have opted for Larch/C++ [34]. While this concrete BISL interacts with C++, BISLs are also available for other programming languages, e.g., for Java [29]. Hence, conceptually, our approach is language-independent.

3.1 Informal explanation of services

Before we discuss the Larch/C++ formalism and we employ it for the specification of our running example, we explain the services provided by the MasterClock object and the ZonalClock objects in an informal manner. Besides the object which provides a service, we often also need to point out further involved objects. To give an example, the
service that creates a *ZonalClock* object forms part of role specification of the *ZonalClock* object, and the service involves the *MasterClock* object to attach the *ZonalClock* object to the *MasterClock* object. There are the following services:

- **MasterClock**: This object provides an interface for attaching and detaching *ZonalClock* objects. The services include the *SetSecond* method to update itself every second, the *SetZonalClocks* method to send notification to the *ZonalClocks* when the *MasterClock*’s time changes, the *SetChange* method to update its time and notify its *ZonalClocks* of time change, and the *GetTime* method to query the current time corresponding to the Greenwich Meridian Time.

- **ZonalClock**: This object provides an interface for creation so that a new instance is attached to a *MasterClock* object, and it also provides an updating interface to keep its state, namely its zonal time, consistent with the *MasterClock*’s state via the methods *UpdateZonalClock* and *SetZonalTime*.

Pseudo-code as used in UML would come close to such an informal definition. In addition, certain UML diagram forms could be used, e.g., collaboration diagrams or sequence diagrams. In our three-tiered specification approach, we want to provide *behavioural* specifications of the services.

### 3.2 Behavioural interface specification in Larch/C++

An object’s role specification defines a number of roles (say, interface functions, or methods for short). To this end, we have to indicate which trait it uses. This trait provides the names and meanings of the operators referred to in the definition of the interface functions. Each such definition consists of a *header* and a *body*. The header specifies the name of the interface function, the names and types of parameters, as well as the return type (if any). We use the same notation as in Larch/C++ [30]. The body consists of an *ensures* clause as well as optional *requires* and *modifies* clauses. The *requires* and *ensures* clauses specify the pre- and post-condition respectively. The identifier *self* in the those assertions denotes the object that receives the corresponding message. The *modifies* clause lists those objects whose value may change as a result of executing the method. An omitted *modifies* clause is interpreted to mean that no object is modified—neither *self* nor any parameter objects. Finally notice the following conventions for referring to values and states in role specifications:

- A distinction is made between an object and its value by using an unannotated identifier (for example, *s*) to denote an object, and a superscripted object identifier (for example, *s*” or *s’*) to denote its value in a state.

- The postfix operators “” and “” for superscripting are used to extract values from objects. An object identifier superscripted by “” denotes an object’s initial value and an object superscripted by “” denotes its final value.

- The terms *pre* and *post* refers to the state just before or after the invocation of the specified method, respectively. The term *any* can be used when either of these will do. Each of these has the sort *State* which is the sort of the formal model of states in Larch/C++. If we want to access the value of an object *o* in a state *st*, then we use the notation *o\st", e.g., self\any."
**MasterClock** : role specification

uses WorldClock

Attach(z: ZonalClock) {
    modifies zonalClocksOf(self);
    ensures z ∈ zonalClocksOf(self);
}

Detach(z: ZonalClock) {
    requires z ∈ zonalClocksOf(self);
    modifies zonalClocksOf(self);
    ensures z /∈ zonalClocksOf(self);
}

Int GetTime() {
    ensures result = toInt(currentTime(self\any));
}

SetSecond() {
    modifies self;
    ensures self′ = succ(self);
}

SetZonalClocks() {
    modifies containedObjects(zonalClocksOf(self), pre);
    ensures ∀z : ZonalClock (z ∈ zonalClocksOf(self) ⇒ isConsistent(self, z, post));
}

SetChange() {
    modifies self ∧ containedObjects(zonalClocksOf(self), pre);
    ensures self′ = succ(self) ∧ ∀z : ZonalClock
        (z ∈ zonalClocksOf(self) ⇒ isConsistent(self, z, post));
}

Fig. 6. Role specification of MasterClock objects using the WorldClock trait

3.3 Roles of the clock objects in the WorldClock micro-architecture

In Fig. 6 and Fig. 7, the role specifications of MasterClock and ZonalClock objects are specified. The formal specifications directly implement our earlier informal explanations. Note how the operations from the lowest tier are employed.

4 Highest tier: Interaction

The highest tier employs the lower tiers to provide a specification of the interaction among the collaborating objects. The interaction between services provided in their roles must be specified in terms of operation sequences, and flow of control. These specify the state transformations of the object collaboration. In our formal specification approach, we use a simple designated action calculus for the interaction layer.
**ZonalClock** : role specification

uses WorldClock

ZonalClock(m: MasterClock) {
    constructs self;
    ensures masterOf(self) = m;
}

UpdateZonalClock() {
    modifies self;
    ensures isConsistent(masterOf(self), self, post);
}

SetZonalTime(i:Int) {
    modifies self;
    ensures self' = update(fromInt(i), self');
}

---

**Fig. 7.** Role specification of ZonalClock objects using the WorldClock traits

### 4.1 Sequence diagrams

Before we discuss the formal specification of interaction, we recall the diagrammatic UML approach used in OOD. In Fig. 8, we illustrate a collaboration scenario for the WorldClock micro-architecture using a sequence diagram. We illustrate how aMasterClock interacts with aZonalClock and anotherZonalClock. It is not possible to capture that there could be arbitrarily many ZonalClock objects, and that the updates for all ZonalClock objects could be done independent of each other, in parallel. We do not claim that such a diagrammatic is inherently informal. In fact, there are efforts to assign a formal and useful semantics to sequence diagrams and other UML notations. However, an inherent problem with formalising, using, and supporting UML is its complexity. We also refer to [34] for a critical review of UML’s suitability for the specification of design structures such as design patterns. We contend that our simple formal approach is complementary to UML.

### 4.2 Classification of actions

The interaction of collaborating objects will be specified using a logic of actions like Lamport’s Temporal Logic of Actions [24]. Before we deal with the actual forms of actions, we want to classify actions to gain a better understanding of interaction, and of the process in which smaller behaviours contribute to interactive behaviour. A simple action is in our case an invocation of a role of an object. Then, a compound action is composed from simpler actions by sequential composition and other means. Let us categorise actions regarding their possible effects. We first focus on categories of simple actions, that is, method invocations, or methods for short. The following categories capture whether a method affects the state of the associated object, or the objects in the environment, and whether the execution of the method returns a value:
Fig. 8. Sequence diagram for the WorldClock example

- A $V$-method returns a value.
- An $O$-method changes the abstract state of the object itself.
- An $E$-method changes the abstract state of the object’s environment.

The categories $V$ and $O$ were inspired by a related categorisation in [4]. By an object’s environment, we shall mean any object other than the given object which is related in some way to the given object. The differentiated categories $O$ and $E$ provide a more precise characterisation of the role behaviour. We assume that a method which belongs to the $E$-category must always also belong to the $O$-category, so that any change in the environmental state of an object is reflected by a change in the abstract state of the object itself. Further, we assume that methods which both perform state change and return a value can be reduced to methods which separate these concerns. Consequently, we assert that the role specifications from the middle tier are defined only with actions of the canonical combinations $O$, $O-E$, and $V$. To give an example, one can easily observe the following categories for the role specification of MasterClock objects in Fig. 8:

- $O$: Attach, Detach, SetSecond
- $O-E$: SetZonalClocks, SetChange
- $V$: GetTime

Slightly different kinds of categories had to be considered for compound actions because they are typically concerned with several objects at a time. However, one could still define the environment of a given set of objects, and one could also consider the state local to a set of objects. We should assume a notion of atomicity for compound actions, that is, the intermediate state changes which are caused by steps of execution are not observable, but only the final state. A value-returning compound action could also be characterised easily.
4.3 Action combinators

An interaction specification defines actions on certain collaborating objects in terms of action combinators like independent or sequential collaboration. We group such definitions per class. A single definition of an interaction is given as a method definition. The object the method of which is invoked and the objects occurring as method arguments are said to participate in an interaction. There is the following (abstract) syntax for interaction specifications:

\[
\begin{align*}
s & ::= \text{class } c \{ \text{ i* } \} \quad (\text{Interaction specifications}) \\
i & ::= \text{method } m \{ \text{ v* } \} \{ \text{ a } \} \quad (\text{Method definitions}) \\
p & ::= v : t \quad (\text{Parameters}) \\
a & ::= \text{ (Actions) } \\
\quad e.m ( e* ) \quad (\text{Method invocation}) \\
\quad | a \land a \quad (\text{Independent composition}) \\
\quad | a ; a \quad (\text{Sequential composition}) \\
\quad | a \| a \quad (\text{Composition by choice}) \\
\quad | \text{let } v = a \text{ in } a \quad (\text{Substitution}) \\
\quad | \text{if } g \text{ then } a \quad (\text{Guarded action}) \\
\quad | \text{while } g \text{ do } a \quad (\text{Iterated action}) \\
e & ::= \text{ (Expressions) } \\
\quad v \quad (\text{Instance variable}) \\
\quad y \quad (\text{Yielder})
\end{align*}
\]

This notation immediately suggests that interaction specifications can be simulated, say executed. A simple action is of the form “e.m(...))”, and it denotes the object invocation restricted by pre- and post-condition of the role specification \(m\) for the object \(e\) given in the middle tier. An expression \(e\) is either an instance variable \(v\), e.g., \(self\), or a yielder, that is, the application of an operator from the lowest tier that yields an object (reference). We adopt the common convention to omit “self” in simple actions.

There are three fundamental ways of binary action composition. Sequential composition is used if the order of state changes matters, either because the actions operate on the same object (cf. category \(O\)), or they operate on an overlapping part of the environment (cf. category \(E\)). By contrast, independent or parallel composition is used if the two actions do deliberately not interfere each other, that is, they operate on different “regions” of the state space. Finally, choice selects one out of two actions depending on which pre-condition evaluates to true. In the case that both pre-conditions evaluate to true, we deal with non-deterministic choice. The semantics of these forms of compound actions is defined as follows:

\[
\begin{align*}
\text{Action } a_0 & \quad \text{Pre-/Postcondition} \\
\text{ } a_1 \land a_2 & \quad (\text{pre}(a_0) \Rightarrow \text{pre}(a_1) \land \text{pre}(a_2)) \land (\text{post}(a_1) \land \text{post}(a_2) \Rightarrow \text{post}(a_0)) \\
\text{ } a_1 ; a_2 & \quad (\text{pre}(a_0) \Rightarrow \text{pre}(a_1)) \land (\text{post}(a_1) \Rightarrow \text{pre}(a_2)) \land (\text{post}(a_2) \Rightarrow \text{post}(a_0)) \\
\text{ } a_1 \| a_2 & \quad ((\text{pre}(a_0) \Rightarrow \text{pre}(a_1)) \Rightarrow (\text{post}(a_1) \Rightarrow \text{post}(a_0))) \\
& \quad \lor ((\text{pre}(a_0) \Rightarrow \text{pre}(a_2)) \Rightarrow (\text{post}(a_2) \Rightarrow \text{post}(a_0)))
\end{align*}
\]

We can generalise the two commutative, associative combinators for independent composition and choice to distributed versions accepting a set of actions as opposed to just two actions. The form “let \(v = a_1 \text{ in } a_2\)” can be regarded as sequential composition with substitution: every occurrence of \(v\) in \(a_2\) is substituted by \(a_1\), and
class MasterClock {
  method SetZonalClocks() { \( \land z \in \text{zonalClocksOf}(self) \). UpdateZonalClock() }
  method SetChange() { SetSecond(); SetZonalClocks() }
}

class ZonalClock {
  method ZonalClock(m : MasterClock) { m.Attach(self) }
  method UpdateZonalClock() { if \( \neg \text{isConsistent(masterOf(self), self, pre)} \) then let \( i : \text{Int} = \text{masterOf(self)}.\text{GetTime}() \) in SetZonalTime(i) }
}

Fig. 9. Interaction specification for WorldClock example

then the action \( a_2 \) is performed. For simplicity, we might assume that \( a_1 \) is a simple, purely value-returning action (i.e., a \( \forall \)-method).

There are two more combinators dealing with guarded and iterated actions. The action \( a_1 \) in “if \( g \) then \( a_1 \)” is executed iff the guard \( g \) can be passed. As an aside, parallel collaboration can be used to define an “if \( g \) then . . . else . . .” if needed. The action “while \( g \) do \( a_1 \)” denotes a loop with pre-test. That is, the action \( a_1 \) is repeatedly performed as long as the guard \( g \) can be passed. Guards are applications of Boolean operators defined in the lowest tier. The semantics of \( \text{if} \) and \( \text{while} \) is the following:

| Action \( a_0 \) | Pre-/Postcondition |
|-----------------|-------------------|
| if \( g \) then \( a_1 \) | \( ((\text{pre}(a_0) \land G \Rightarrow \text{pre}(a_1)) \Rightarrow (\text{post}(a_1) \Rightarrow \text{post}(a_0))) \) \lor \( (\text{pre}(a_0) \land \neg G \Rightarrow \text{post}(a_0)) \) |
| while \( g \) do \( a_1 \) | \( (\text{pre}(a_0) \land G \Rightarrow \text{pre}(a_1)) \) \land \( (\text{post}(a_1) \Rightarrow \text{pre}(a_0)) \) \land \( (\text{pre}(a_0) \land \neg G \Rightarrow \text{post}(a_0)) \) |

This ends our exposition of action combinators for the specification of interactions between objects. Note how the tiers in our specification approach are layered. The lowest tier formalises Boolean operators needed for guards of conditionals and loops in the highest tier. The lowest tier also provides operators than can be applied to refer to objects in the interaction specification on the basis of the structural specification. Furthermore, the middle tier provides the roles invoked as the simple actions in the highest tier. Finally note that our set of action combinators for interaction does not include any form of assignment. State changes are solely encapsulated in the role specifications.

4.4 Interaction specification for the WorldClock micro-architecture

Our running example is completed in Fig. 9. In this particular specification, for every name of an interaction, there happens to be an interface function of the same name in the role specifications. Consider, for example, the name SetChange. The role specification SetChange in the middle tier defines the behaviour in terms of pre- and postconditions whereas the method SetChange in the highest tier defines an interaction based on a sequence of two simpler method invocations. This is a checkable redundancy where the two specifications focus on different aspects of the object collaboration. In general, one might define compound actions which merely use services from the role specifications.
Let us highlight some elements of the specification in order to illustrate the action calculus. In the specification of SetZonalClocks, the notation \( \wedge z \in \text{zonalClocksOf}(\text{self}) \ldots \) is used for distributed independent collaboration to point out that the UpdateZonalClock methods can proceed for all the relevant ZonalClocks independently of each other. In the specification of SetChange, sequential collaboration is used because it is essential that the MasterClock object invokes SetSecond and SetZonalClocks subsequently on itself. In the specification of the UpdateZonalClock, there is a guarded action. It models that the role “SetZonalTime(\ldots)” only needs to be invoked if an update is due. The guard relies on the operator isConsistent from the lowest tier. Also, in order to retrieve the MasterClock object associated to self, we use the operator masterOf from the lowest tier. In this manner, we query a structural aspect of the WorldClock micro-architecture. The guarded action performs “SetZonalTime(i)” where i is substituted by the time that is obtained via an invocation of “masterOf(self).GetTime()”.

5 Related work

A good specification of the micro-architectures in a framework is indispensable to both the reuser of the framework and to the developer/maintainer of the framework. Yes, it is like saying that “every program must have a specification”. If a reuser of the framework has to understand the framework, either the reuser could look at its underlying design patterns (which are very abstract), or (s)he could read the code to extract some behavioural insight (which is a waste of time). We contend that specifications of micro-architectures complement high-level designs such as UML diagrams, and that this marriage explains the behaviour of objects in the framework in an appropriate manner. Let us consider previous work on specification of object-oriented designs.

In [28], UML notation for class and sequence diagrams is enriched by certain precise visual constraints which are useful for design-pattern descriptions. In order to specify, for example, that a certain participating class can occur several times in an actual pattern instance, suitable Venn diagrams are used. This is an improvement over the style used in the GoF catalogue [20] where such constraints are treated in an informal manner, e.g., by giving an example with two sample classes. The enriched UML sequence diagrams covers in part the aspects captured in the middle and the highest tier in our approach. However, behavioural specifications are not an issue, neither does this UML approach adhere to a layered specification discipline.

In [27], various design patterns are formally proved to be refinement transformations in a semantical sense when compared to a more native/hard-wired encoding of the corresponding design pattern. To this end, an object calculus theory [15] is used as the semantical framework. This formal model does not aid the reusable behavioural specification of micro-architectures, nor does it address the issue of object interaction. The work is geared towards a representation of design patterns in formal specifications for purposes of semantical reasoning.

In [24], a logic on parse trees is used to specify and enforce constraints on a design language. One can deal with architectural characteristics, or even with source code requirements in this manner. One possible application is to use the logic in order to enforce invariants of design-pattern instantiations. One can also use the mainstream language OCL to describe certain well-formedness constraints on an object-oriented
design or a program. Such approaches emphasise structural or even syntactical invariants of micro-architectures, design patterns, or styles. Specification of behaviour and interaction is beyond the scope of these approaches.

In [31], design patterns are formally specified using the formal specification method DisCo for reactive systems. The formal basis of DisCo is Temporal Logic of Actions [26]. In this setting, actions are understood as multi-object methods. These actions are atomic units of execution. An action consists of a list of participants and parameters, an enabling condition, and the definition of state changes caused by an execution of the action. An important contribution of this work is that it indicates how combination and instantiation of patterns in terms of their defining multi-object methods can be performed. The DisCo specifications roughly correspond to the interaction specifications in the highest tier. However, in our approach, it is essential that the interaction specifications are defined on top of the other layers for structural and behavioural aspects of micro-architectures.

In [13], a specification approach is described to capture design patterns and other building blocks. To this end, a declarative specification language LePUS corresponding to a subset of higher-order logic is employed. The prime idea is to define (say, constrain) object-oriented designs and their building blocks in terms of suitable sets of methods and classes, and relations on these. A non-trivial example is a so-called tribe which is a set of clans, that is, a set of methods which share a signature, in relation to a set of classes. Such a tribe is relevant in the specification of the Visitor pattern [20]. This approach addresses non-trivial structural properties but it is not suited to specify the behaviour of collections of objects, neither does it address object interaction.

In [16], object-oriented designs and design patterns are specified using RSL—the RAISE specification language [35]. This approach addresses weaknesses of informal and diagrammatic approaches in that it helps a designer to demonstrate conclusively that a particular problem matches a particular pattern, or that a proposed solution is consistent with a particular pattern. The proposed type of specification clearly captures more structural properties than a pure class diagram. The formal model also attempts to capture some behavioural characteristics such as the variables changed by a certain method invocation. Still the approach is rather syntactical in that it merely defines well-formedness relations on representations of object-oriented designs. Also, the approach neglects object interaction.

In [23], a significant contribution to the problem of specifying micro-architectures is presented. The authors present a modelling construct called contracts for the specification of behavioural compositions. The paper illustrates that behavioural specifications are meaningful for refinement, conformance testing, and instantiation. The specification language is structured in the sense that different kinds of obligations or constraints are considered, namely typing, behavioural and contractual obligations. When compared to our specification language, contracts do not adhere to the multi-layered principle. Also, no formal syntax and semantics has been given for the specification language. This hampers tool support, and the verification of the correctness of programs that implement the micro-architectures.

To summarise, previous approaches usually focus on only selected aspects of collections of collaborating objects while our approach identifies three different tiers to
achieve full coverage. Most previous approaches involve informal ingredients. This is particularly true for the mainstream UML approach. By contrast, our simple formal approach is accessible for formal testing and verification. That is, Larch/C++ specifications can be tested [1], and properties defined in terms of LSL traits can be verified [2]. Although our specifications are formal, they are immediately useful in the programming phase as supported by the Larch tool suite. Previous approaches usually emphasise the specification of design patterns. Note that behavioural specifications are not too much of an issue for design patterns. Even “behavioural” patterns [20] are rather “algorithm-free”: their vague operational meaning is usually indicated via pseudo-code, and it can hardly be captured with specifications using pre- and postconditions or otherwise. By contrast, we focus on micro-architectures. These building blocks of domain-specific application frameworks usually exhibit some interesting behaviour subject to role specifications in our middle tier.

6 Conclusion

Three-tiered specification Our approach enables the reuser to understand the structural aspects (lowest tier), the behavioural aspects (middle tier) and the interactive aspects (highest tier) of collections of collaborating objects. The specification of behaviour in terms of roles depends on the specification of structural aspects. That is, the operators from the lowest tier are used in the pre- and postconditions in the middle tier. The specification of interaction between the collaborating objects in the highest tier invokes the roles of the objects specified in the middle tier, and operators from the lowest tier are used to query structural aspects. The three tiers achieve a separation of concerns. In each tier, a designated notation is favoured. Structural aspects are preferably specified in algebraic style as supported by LSL. Behavioural aspects are best described by contracts based on pre- and postconditions as supported by Larch/C++. Finally, the interaction of collaborating objects is best captured by an action calculus, say, a TLA-like logic. The approach adheres to a layered architecture principle. Lower tier specifications are imported into the next higher tier. Inclusion of a component from a higher tier to a component in a lower tier is not permitted, that is, there are no up-calls. This design permits improved reuse of components, and it allows changes to components in one layer without affecting the components in lower layers. In previous studies [1,2,3], we have investigated the virtues of different variations on a three-tiered system architecture, and we have shown its expressiveness for the development of real-time reactive systems, E-Commerce systems, and evolving systems. For instance, the three tiers of a reactive system architecture respectively contain specifications of abstract data types, reactive classes, and system configurations. The contribution of the present paper is to capture our experience in a three-tiered specification approach.

Evolving systems Let us indicate how our specification approach enables the evolution of a software system when requirements are revised or new ones need to be added. This will further clarify the usefulness of the specification approach in practice. System evolution is partitioned horizontally as well as vertically: evolution can happen in each tier, and propagation of change is across two successive tiers. To slightly generalise our WorldClock example from before, let us consider a system which involves publishers and subscribers instead of MasterClocks and ZonalClocks. This more abstract scenario
corresponds to the Observer pattern [20], also known as Publisher-Subscriber pattern. The pattern basically suggests that a publisher notifies any number of subscribers about changes to its state. Our layered specification approach offers the following advantages if a system involving publishers and subscribers evolves:

– Traits can be refined for whatever reason of evolution in the first tier, and a refined trait may be included in a role specification to enrich the theory or strengthen data structuring. To give a simple example, if it is required for a publisher to maintain an ordered list of currently subscribed components, the Set trait can be refined to List in the first tier, and the List trait is then linked to the role specification. In general, changes which are local to the first tier, can be analysed prior to their propagation to the second tier. Refinement mappings for Larch traits are discussed in [12].

– An object can take both roles, that of a publisher as well as a subscriber, because in principle an object can subscribe to several publishers, and an object subscribing to a publisher may itself be a publisher for some other objects. If such a combination of responsibilities or services is required, then this is easy to achieve because role specifications in the second tier can be linked to several traits via the uses clause. Without layering, such requirements are difficult to model in a formal manner.

– The publisher may decide which internal state changes it wants to share with its subscribers. It may also decide when and how to communicate such changes. These decisions are manifested in the role specification of the publisher. A revision of these decisions only requires local modifications in the middle tier. The interaction specification in the third tier will be “automatically” updated with the modified methods. In [1], a theory is given for constructing composite classes and class refinements. Evolution in the second tier would need to satisfy a similar theory.

– Suppose the requirement of the publisher evolves such that the publisher is required to communicate state changes to its subscribers without the subscribers knowing the identity of the publisher. Then, we need to introduce a new role specification in the second tier, say Channel. In addition, the interaction components in the third tier have to be revised as follows:
  • the publisher interacts with the channel, and
  • the channel interacts with subscribers.

Towards an integrated development method Each tier in our specification approach gives rise to an implementation layer. Also, the presented specification approach allows for a seamless integration of the three tiers with UML visual modelling facilities, automated testing of Larch/C++ specifications [11], and verification of properties defined in terms of LSL traits [22]. The components in each layer can be individually analysed before before composition, adaptation, or reuse. It turns out that one important notion is missing in our layered approach to the specification of micro-architectures: we lack a sufficiently expressive and automated model for reuse of class structures. That is, to actually deploy reusable micro-architectures or even design patterns in an actual application context, we need language constructs, tool support, and other means to adapt library structures, to replicate participants in a collaboration, to refine micro-architectures, and to compose behaviours of micro-architectures. In our ongoing research, we attempt to reuse ideas from programming support for design patterns [8,9,6,7,10,18] and corresponding ideas for tool support for OOA/OOD/OOP [17,34,19]. In particular, we plan
to base the syntactical notion of reuse on superimposition of class structures as defined in our previous work [10,18,19]. This will eventually lead to a fully integrated software development method centered around the notion of micro-architectures.

Acknowledgement The first author is grateful for the collaboration with Sridhar Narayanan who contributed to the subject of the paper in an important way.

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