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Credo Methodology*

Modeling and Analyzing A Peer-to-Peer System in Credo

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Abstract

Credo offers tools and techniques to model and analyze highly reconfigurable distributed systems. In this paper, we present an integrated methodology to use the *Credo* tool suite. In this methodology, we advertise the use of top-down design, component-based modeling and compositional analysis to address the complexity of highly reconfigurable distributed systems. As a running example, we model a peer-to-peer file-sharing system and show how and when to apply the different modeling and analysis techniques of *Credo*.

Keywords: distributed systems, dynamic reconfiguration, compositional verification, testing, schedulability analysis

1 Introduction

Current software development methodologies follow a component-based approach in modeling distributed systems. A major shortcoming of the existing methods is the lack of an integrated formalism to model highly reconfigurable distributed systems at different phases of design, i.e., systems that can be reconfigured in terms of a change to the network structure or an update to the components. Moreover, the high complexity of such systems requires tool-supported analysis techniques.

In this paper, we integrate the *Credo* tools and techniques into the software development life-cycle. We illustrate how and when to use them during the design and

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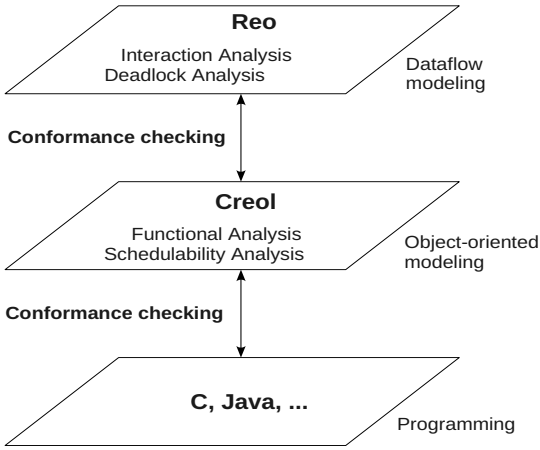


Fig. 1. Overview of modeling levels and analysis in *Credo*

analysis phases. Thus, software engineers can benefit by enriching their preferred methodology with the *Credo* tool suite.

The core of the *Credo* tool suite consists of two different *executable* modeling languages: Reo [2] is an executable *dataflow* language for high-level description of dynamic reconfigurable *networks* connecting components; Creol [13] is an *object-oriented* modeling language, used to provide an abstract but executable model of the implementation of the individual components. Fig. 1 illustrates the relation between these modeling languages and their relation to existing programming languages. It also indicates the kind of analysis the *Credo* tool suite provides for each modeling language.

To support top-down design and compositional analysis, we make use of *behavioral interfaces* for the different abstraction levels of the design (cf. Fig. 2). At

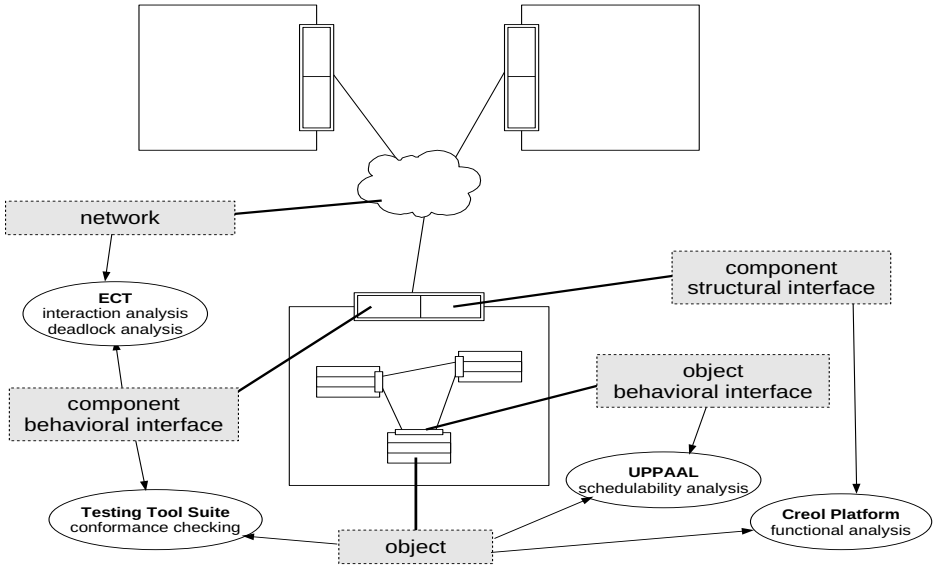


Fig. 2. End user perspective of the *Credo* Tools

the top-level, behavioral interfaces are used to describe the dataflow between the components of a system. These interfaces abstract from the details of the internal object-oriented model of components. Instead they describe the kind of connections components use to communicate and interact. *Credo* provides as an Eclipse plug-in an integrated tool-suite, ECT (Eclipse Coordination Tools) [6], to model and analyze the interactions between the components in a given network, e.g., absence of deadlock can be checked at an early stage of design.

The functional behavior of the objects within a component is modeled in Creol. The conformance between such a model of a component and its behavioral interface can be checked in *Credo* [8]. On the other hand, given an implementation of a component in a programming language like C, *Credo* also provides a technique to check for conformance between the implementation and the model [9,1]. Both techniques are based on *testing* and use the behavioral interface as an abstract model to generate test cases and to control the execution of the test cases.

Furthermore, the *Credo* tool suite offers an automated technique for *schedulability analysis* of individual objects [12,11]. We use the *timed automata* of UPPAAL to model objects and their behavioral interfaces. Given a specification of a scheduling policy (e.g., shortest deadline first) for an object, we use UPPAAL to analyze the object with respect to its behavioral interface in order to ensure that tasks are accomplished within their specified deadlines.

We illustrate the *Credo* methodology with an example. We model and analyze a file-sharing system with hybrid peer-to-peer architecture (like in Napster), where a central server keeps track of the data in every node. In Section 2, we develop the structural and behavioral interfaces of the components (nodes of the peer-to-peer system) and the network (the broker managing the dynamic connections between nodes); and prove our model of the network to be deadlock free. In Section 3, we give executable Creol models for the components and analyze them by means of simulation and testing for conformance both with respect to the behavioral interfaces and an implementation. We demonstrate schedulability analysis by analyzing the broker. In Section 4 we conclude the paper.

2 High-Level Dataflow Modeling

Reo [2] is a channel-based coordination model for component composition. As the formal semantics of Reo, we use constraint automata [3]. In Reo, a system consists of a set of components connected by a network. The network exogenously controls

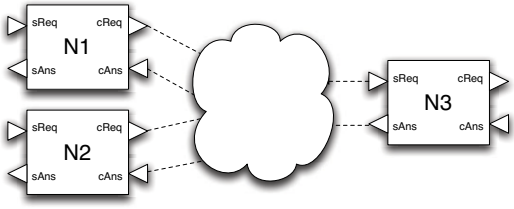


Fig. 3. Nodes in the peer-to-peer system

the data-flow between the components and may be dynamically reconfigured to alter the connections between the components. At this level of abstraction, only a *facade* of each component is visible. A facade consists of port and event declarations, and its abstract behavior is specified using constraint automata. In this paper, we do not go into the details of how to compose Reo channels. Instead, we model the network behavior directly using constraint automata.

Components use ports to communicate with each other via the network. Fig. 3 shows a system of components (as rectangles), their ports (as small triangles), and the network (as a cloud). Ports can be either inports or outports (implied by the direction of the triangles). By exogenous coordination, we mean that a component has no direct control on how its ports are connected. A component can only indirectly influence its connections by raising events. Events include requests/announcements of services, time-outs, or acknowledgments. These events can trigger reconfigurations of the *context-aware* network. The network includes a network manager that handles events and reconfigures the network according to the events.

In this section, we model the nodes of the peer-to-peer system as components. The network consists of the broker that manages the connections between the component ports. Each node has two sides, a client side and a server side. On each side, a pair of request and answer ports is needed. As a client, a node writes a request to cReq and expects the result on cAns. As a server, a node reads a request (a 'key' identifying the reuqested data) from sReq and writes the result to sAns. For two nodes to communicate, the broker has to connect the corresponding ports of the client and the server.

2.1 Structural Interface Description

To describe the facade of a component, we declare its ports and the events the component may raise. Below, we define two facades, ClientSide and ServerSide. The facade Peer inherits the ports and events declared in these two and adds another event that is needed when the two sides are combined.

```
facade ClientSide begin
  port cReq : outport
  port cAns : inport
  sync_event openCS<req:outport,ans:inport>(in k:Data; out f:Bool)
  sync_event closeCS<req:outport,ans:inport>()
end
```

```
facade ServerSide begin
  port sReq : inport
  port sAns : outport
  sync_event openSS<req:inport,ans:outport>()
  sync_event closeSS<req:inport,ans:outport>()
  register<>(in keyList : List[Data]) // async_event
end
```

```
facade Peer inherits ClientSide, ServerSide begin
  update<>(in keyList : List[Data])   // async_event
end
```

The network manager does not keep a centralized account of all port bindings; these are locally stored at each component. A component cannot directly change its port bindings. Before using ports, the component must request a connection by raising an open session event. An event for closing the session implies that the ports are ready to be disconnected. These events must provide the ports to be used in the session as parameters. In addition, they can have extra parameters, e.g., the 'open client session' event (written as openCS) guides the connection by providing the key it is looking for, and in return it is informed whether such a node is found.

Events are by default asynchronous. However, when expecting return values (e.g., opening or closing a session), we declare events to be synchronous (using the keyword **sync_event**). All events raised by the components are handled by the network. This is reflected in the structural interface description of the network.

2.1.1 Network

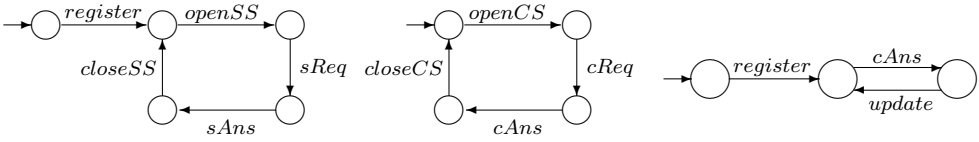
We give the structural interface description of a particular network manager called Broker. The keyword **networkmanager** is used to identify such interfaces (and distinguish them from those characterizing component facades). The *Credo* methodology distinguishes between the concept of a network manager and the network itself because a network in general consists of a network manager and additional coordination artifacts like *channels*, as described later in this section. The description of the Broker declares the event handlers that it provides. For each event handler, it specifies the facade (representing a component) from which the handled event originated using the keyword **with**.

```
1  networkmanager Broker begin
2     with ServerSide
3        register<>(in keyList : List[Data])
4        sync_event openSS<in req:inport,ans:outport>()
5        sync_event closeSS<in req:inport,ans:outport>()
6     with ClientSide
7        sync_event openCS<in req:outport,ans:inport>(in k:Data; out f:Bool)
8        sync_event closeCS<in req:outport,ans:inport>()
9     with Peer
10       update<>(in keyList : List[Data])
11 end
```

2.2 Behavioral Interface Description

The behavioral description for a component facade comprises of specifying the order of raising events and the port operations. This is modeled using constraint automata [3]. In these automata, we denote port operations by specifying the port names. The corresponding action (read or write) is understood from the port type (given in the structural facade description).

Fig. 4 shows the behavioral specification for the facades in our example. As mentioned earlier, the port actions are surrounded by opening and closing session events in parts (a) and (b) of this figure. A server registers its data with the broker to initialize its operation. We opt for a simple scenario, i.e., each server or client



(a) ServerSide (b) ClientSide (c) Peer

Fig. 4. Behavioral interfaces for facades

handles only one request at a time. We also assume at this level of abstraction, that openCS is always successful, i.e., every data item searched for is available.

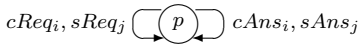
The Peer facade inherits the behavior specified for ClientSide and ServerSide facades. The Peer facade introduces some additional behavior, i.e., an update to the data stored at the broker. The Peer automaton (see Fig. 4-c) synchronizes with the ServerSide automaton (see Fig. 4-a) to ensure that an update only takes place after the data is registered. Moreover, the data at the broker is updated after receiving new information (on the ClientSide). This is modeled by synchronization on the read operations on *cAns*.

In general, the behavior of the sub-type has to be a refinement of the behavior of its super-type [16]. This is achieved by computing the product of the automata describing the inherited behavior (ServerSide and ClientSide) and the automaton synchronizing them (Peer). In this product [3] transitions with different action names are interleaved while those with common action names are interleaved while those with common action names are synchronized.

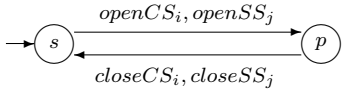
2.2.1 Network

The Broker in a peer-to-peer system connects the ports and handles the events of the components. We show how to model the synchronization of a system consisting of a fixed number of components, say n, for some $n > 0$. The observable actions of the ith component ($i \in \{1, \ldots, n\}$), i.e., the communications on its ports and its events, are denoted by $openCS_i$, $openSS_i$, $closeCS_i$, $closeSS_i$, $cReq_i$, $sReq_i$, $cAns_i$, and $sAns_i$. Synchronization of actions is modeled in the following automata by a transition labeled with the participating actions.

For clarity, we start with different automata for the synchronization of ports and events. Synchronization between the ports of a pair of components i and j is described by the following automaton.



For each pair of components i and j, the following automaton synchronizes the events $openCS_i$ and $openSS_j$ to establish a connection between components i and j and the events $closeCS_i$ and $closeSS_j$ to release the connection again. These two consecutive synchronizations together thus model one session between the client of component i and the server of component j.



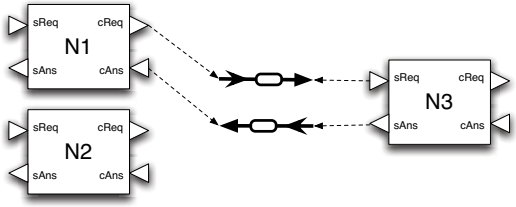
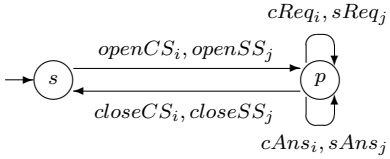


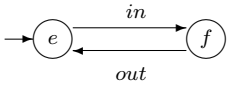
Fig. 5. Using Reo channels for modeling the network.

Combining the automata above models the port connections in a session (shown below). The *interleaving product* of these combined automata for all pairs of components results in an automaton describing the behavioral interface of the Broker.

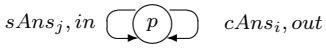


Notice that interleaving allows for components to be involved in more than one session at a time. The *synchronized product* of the Broker automaton with the component automata (from the previous subsection) describes the overall behavior of the system. This product constrains the Broker such that components are involved in at most one session at a time. We model the system and analyze it with the Vereofy tool [14,4], e.g., to ensure absence of deadlock. Furthermore, Vereofy includes symbolic model checking tools for linear-time, branching-time and alternating-time temporal logics with special operators to reason about the events and data flow at ports of components. Due to lack of space, we do not explain the details of such analyses.

Channels. We further refine the network model by introducing *channels* (which are a specific kind of connectors) [2,10]. In general, a channel provides two (channel)-*ends*. We distinguish between input-ends (to which a component can *write*) and output-ends (from which a component can *read*). We also describe the synchronization between the two channel-ends by an automaton. For example, the automaton below models a 1-place buffer. It provides an input-end *in* and an output-end *out*. In state e the buffer is empty and in state f it is full (for simplicity, we abstract from the data transfered and stored).



We model the data-transfer from server j to client i, i.e., the connection between the answer ports, by replacing the synchronization of $cAns_i$ and $sAns_j$ by the following synchronization with the above 1-place buffer.



The overall behavior of the system is described by the synchronized product of

the Broker, the component automata, and the channel automata. The network itself consists of the Broker and the channels. Fig. 5 shows a configuration in which two buffer channels are used as the network connecting the components. The dashed arrows in this figure show port bindings, i.e., the channel-end to which a port is bound. The bold arrows represent the channels. Vereofy can be used also to analyze complex networks containing Reo channels.

3 Object-Oriented Modeling

In this section, we model the components in Creol, an executable modeling language. To model the components, we provide interfaces for the intra-component communication and a Creol implementation of the components. Together with a Creol implementation of the network manager, we get an executable model of the whole system. Since Creol models are executable we use the terms Creol model and Creol implementation interchangeably.

We use intra-component interfaces together with the behavioral interfaces of Section 2.2 to derive test specifications to check for conformance between the behavioral models and the Creol implementation. We also use this specification to simulate the environment of a component while developing the component.

Given a C implementation of the system, we use the behavioral interfaces of Section 2.2 to derive test scenarios to check for conformance between the Creol model and an implementation in an actual programming language. The coverage of these test scenarios is improved by symbolic execution of the Creol implementation.

Finally, we model the real-time aspects of the system using timed automata. In the real-time model, we add scheduling policies to the objects. Here, we check for schedulability, i.e., whether the tasks can be accomplished within their deadlines.

3.1 Executable Creol Model

Creol is an executable modeling language suited for distributed systems. Types are separated from classes, instead (behavioral) interfaces are used to type objects. Objects are concurrent, i.e., conceptually, each object encapsulates its own processor. Creol objects can have active behavior, i.e., during object creation a designated `run` method is invoked.

Creol allows for flexible object interaction based on asynchronous method calls, explicit synchronization points, and underspecified (i.e., nondeterministic) local scheduling of the processes within an object. Creol supports software evolution by means of runtime class updates [18]. This allows for runtime reconfiguration of the components. To facilitate the exogenous coordination of the components we have extended Creol with facades and an event system (cf. Section 2.1).

The modeling language is supported by an Eclipse modeling and analysis environment which includes a compiler and type-checker, a simulation platform based on Maude [5], which allows both closed world and open world simulation as well as guided simulation, and a graphic display of the simulations.

In the rest of this section, we specify the interfaces of a local data store for a peer syntactically. Then, we implement parts of a peer as an example.

Each peer consists of a client object, a server object and a data-store object. The Client interface provides the user with a search operation. The data-store provides the client object with an add operation to introduce new data and the server object with a find operation to retrieve data. We model these two perspectives on the data-store by two interfaces StoreClientPerspective and StoreServerPerspective.

The interfaces are structured in terms of inheritance and cointerface requirements. The cointerface of a method (denoted by the **with** keyword) is a static restriction on the objects that may call the method. In the model, the cointerface reflects the intended user of an interface. In Creol, object references are always typed by interfaces. The caller of a method is available via the implicit variable **caller**. Specifying a concrete cointerface allows for callbacks. Finally, method parameters are separated into input and output parameters, using **in** and **out** keywords, respectively.

```
1 interface StoreClientPerspective begin
2  with Client
3   op add(in key:Data, info:Data)
4 end

6 interface StoreServerPerspective begin
7  with Server
8   op find(in key:Data; out info:Data)
9 end

11 interface Store
12  inherits StoreClientPerspective, StoreServerPerspective
13 begin end
```

The interfaces cover the intra-component communication while the facades cover the inter-component communication (cf. Section 2.1). To implement a Creol class, we can use only the ports and events specified in the facades. Note that the use of ports is restricted to reading from an inport or writing to an outport. Since the inter-component communication is coordinated exogenously by the network, the components are not allowed to alter the port bindings; instead, they have to raise an event to request a reconfiguration of the communication network structure.

Next, we provide implementation models for the interfaces in terms of Creol classes. The client offers a search method to the user. To perform a search, the client makes a request to the broker. The event openCS<req, ans>(key; found) provides the ports req and ans to be reconfigured, plus the parameters key and found. If the data identified by key is available, the broker connects the given ports to a server holding the data and reports via found the success of the search. Otherwise, the ports are left unchanged and the failure is reported via found. If successful the client expects its ports to be connected properly and communicates the data via its ports.

For simplicity, a client only operates one search at a time. Nevertheless, the user can issue multiple concurrent search requests. The requests are buffered and served

in an arbitrary order (due to the nondeterministic scheduling policy) one at a time.

```
1  class ClientImp (store:StoreClientPerspective, req:outport, ans:inport)
2     inside Peer implements Client begin

4     with User op search(in key:Data out result:Data) ==
5        var found : Boolean;
6        raise_event openCS<req, ans>(key; found);
7        if (found) then
8           req.write(key;);
9           ans.take(;result);
10          ! store.add(key, result)
11       end;
12       raise_event closeCS<req, ans>()
13 end
```

To obtain the result of the search, the client uses a synchronous call to the ans port. The update regarding the new data is sent to the data-store asynchronously ! store.add(key, result). Using asynchronous communication the client can already continue execution while the data-store is busy processing the changes. The client is a passive object, i.e., it does not specify a run method.

The server object is active in the sense that it starts its operation upon creation. The active behavior is specified in the run method. This involves reading data requests from the req port and delivering the results on the ans port. To repeat the process, the run method issues an asynchronous self call before termination.

```
1  class ServerImp (store:StoreServerPerspective, req:inport, ans:outport)
2        inside Peer implements Server
3  begin
4     op run ==
5        var key, result:Data;
6        raise_event openSS<req, ans>();
7        req.take(;key);
8        store.find (key; result);
9        ans.write(result;);
10       raise_event closeSS<req, ans>();
11       ! run ()
12 end
```

By raising the event openSS<req,ans>(), a server announces its availability to the broker. This synchronous event returns whenever a request is made for some data on this server. Having provided the ports along the event, the server object expects to be connected to the requesting client, and reads the key to the requested data from its req port. The server looks up the data corresponding to the *key* in the data-store using the find operation. The result is sent back on the ans port. The event *closeSS* announces the accomplishment of the transaction. Finally, the server prepares for a new session by calling the run method again.

3.2 Validation of the Model

Creol programs and models can be *executed* using the rewriting logic of Maude [5]. Maude offers different modes of rewriting and additional capabilities for validation, e.g., a search command and the means for model checking. Credo offers techniques to analyze *parts* of the system in isolation; on the lowest level, to analyze the behavior of a single (active) object in isolation.

Credo offers techniques to analyze, in a black-box manner, the behavior of a component modeled in Creol, by interaction via message passing. This allows for the description and analysis of systems in a divide-and-conquer manner. Thus the developer has the choice of developing the system bottom-up or top-down.

Although Creol allows modeling systems on a high level, the complete model might still be too large to be analyzed or validated as a whole. By building upon the analysis of the individual components, compositional reasoning still allows us to validate the system.

3.2.1 Conformance Testing of the Model

In the context of the Creol concurrency model, especially the *asynchrony* poses a challenge for validation and testing. Following the black-box methodology, an abstract component *specification* is given in terms of its interaction with the environment. However, in a particular execution, the actual order of outputs issued from the component may not be preserved, due to the asynchronous nature of communication. To solve this problem, the conformance of the output to the specification is checked only up-to a notion of observability [8].

The existing Creol interpreter is combined with an interpreter for the abstract behavior specification language to obtain a *specification-driven interpreter for testing and validation* [8]. It allows for *run-time assertion checking* of the Creol-models, namely for compliance with the abstract specification.

We derive a specification for an object directly from the structural interfaces and the behavioral interfaces. The specification of the implementation of the ServerSide is derived from the facade depicted in Section 2.1 and the behavioral interface depicted in Section 2.2. The facade determines the direction of a communication, i.e., whether it is incoming or outgoing communication. For the specification the direction is inverted - the specification 'interacts' with the object to analyze it. The order of the events is determined by the behavioral interface.

The specification language features, among others, choice (between communication in the same direction, i.e., incoming only or outgoing only) and recursion. As an example, we give the specification of a server:

$$\begin{aligned}\varphi_S = {} & \langle event\ register(keyList)\rangle? \ .\ \mathsf{rec}\ X\ .\ \langle event\ openSS()\rangle? \ .\\ & \langle port\ s.sReq(key)\rangle! \ .\ \langle port\ s.sAns(data)\rangle? \ .\\ & \langle event\ closeSS()\rangle? \ .\ X\end{aligned}$$

To test our executable model ServerImpl for conformance with respect to the behavioral interface description, we translate the specification to Creol and in the next

step to Maude. The specification in Maude is executed together with the model. With the data-store at hand, we specify via the method parameters that the data delivered along the sAns port of the server is actually the data identified by the key. This needs to be done on the level of the Maude code.

The object is executed together with the specification in a special version of the Maude interpreter customized for the testing purpose. The programmer can track down the reason for a problem according to the Maude execution. This can be either a mistake in the executable model or a flaw in the behavioral model, i.e., the specification. The interpreter reports an error if unexpected behavior is observed, i.e., an unspecified communication from the object to the specification, or a deadlock occurs.

3.2.2 Simulation

The conformance testing introduced in the previous section is already a simulation of a part of the system, i.e., the object under test. We use a modified version of the above testing interpreter to eliminate of the error reporting. Notice that the Maude interpreter of Creol is a set of rewrite rules which reduces the modification of the interpreter in this case to the deletion of the rules dealing with the error reporting.

Furthermore, we use the facades and behavioral interfaces of section 2 to derive a Creol skeleton of the network. By filling in the details of the network manager, we get a Creol model of the network. The model of the network and the models of the components together form a model of the entire system, which can be executed in Maude.

We use Maude to steer the execution of the model on different levels. We use the different built-in rewriting strategies to simulate different executions of the system. We use Maude's search command to search for a specific execution leading to a designated program state. And we use Maude's meta-level to control an execution by controlling the application of the rewrite rules.

To supplement the above simulation strategies, we use Maude's *model-checking* facilities. In general, the simulation is non-deterministic, which means, that only part of the specified behavior is covered. Therefore erroneous behavior might be missed. Maude's search facility allows us to explore the search space systematically. A general limitation of model checkers is the state space explosion, which makes larger systems unmanageable, when it comes to model checking. By analyzing *parts* of the system in isolation we reduce the state space explosion. Furthermore, Creol as a modeling language allows us to represent the system in a high-level, abstract manner, and concentrate on the crucial design-choices, which furthermore increases the chances of being able to model-check such a model. Since Maude is based on rewriting, dealing with the asynchronous nature of communication is natural: the asynchronicity is represented by trace–equivalence, which is directly represented as equivalence in the Maude rewriting system. This allows the execution engine to more efficiently represent the state space (by working on the normal forms instead of exploring all re-orderings one by one).

3.2.3 Conformance Testing of the Implementation

We use a formal testing process to provide the necessary links between behavioral interfaces, Creol models, and the actual implementation. Behavioral interfaces provide *test scenarios*, patterns of interactions between the components. A test case created according to a test scenario represents a functional description, but does not guarantee a good coverage of the model. To optimize the coverage, *dynamic symbolic execution* is used to analyzes execution paths through the Creol model to find representative test cases while avoiding redundancies in the test suite [9].

Once a test suite is created, the next step in testing is executing the tests on the implementation and reaching a test verdict to check the conformance between model and implementation. Testing a concurrent system involves validating both functional and nonfunctional aspects. Functional aspects are covered by standard techniques like runtime assertions in the implementation and unit testing. To test the concurrency behavior of an implementation against its model we use the observation that typically the Creol model and the implementation share a common structure with regard to high-level structure and control flow. It is therefore reasonable to assume that, given equivalent stimuli (input data), they will behave in an equivalent way with regard to control flow.

We instrument the implementation to record *events* and use the instrumented implementation to record *traces* of observable events. Then we restrict the execution of the model to these traces. If the model can successfully play back the trace recorded from the implementation (and the implementation produces the correct result(s) without assertion failures), then the test case is successful. The Creol model is used as a test oracle for the execution of the test cases on the actual implementation [1].

3.3 Schedulability Analysis

In this section, we explain how to model the real-time aspects of the peer-to-peer system using timed automata and the Uppaal model checker [15]. An object or component is called schedulable if it can accomplish all its tasks in time, i.e., within their designated deadlines. We demonstrate the schedulability analysis process [7,11] on the broker object in the peer-to-peer model, which is the most heavily loaded entity in this system.

In the real-time model of an object, we add explicit schedulers to object specifications. For schedulability analysis, the model of an object consists of three parts: the behavioral interface, the methods and the scheduler.

Behavioral interface. To analyze an object in isolation, we use the behavioral interface as an abstract model of the environment. Thus, it triggers the object methods. Fig. 6 shows the behavioral interface of the broker augmented with real-time information. The automata in this figure are derived from the behavioral interface of Peer (in Section 2) by removing the port operations. To send messages, we use the invoke channel, with the syntax invoke[message][sender][receiver]!. To specify the deadlines associated to a message, we use the variable deadline.

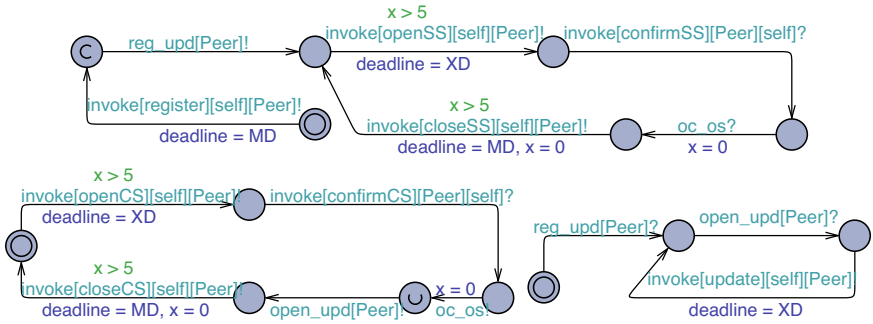


Fig. 6. The behavioral interface of broker modeled in timed automata

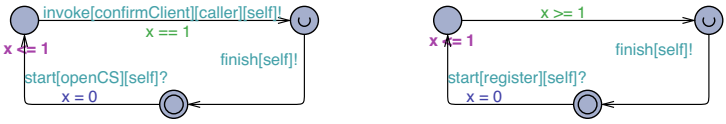


Fig. 7. Method automata for handling openCS and register events

In Fig. 6, we use the open_upd and reg_upd channels to synchronize the automata for Peer with ClientSide and ServerSide, respectively. Additionally, the automata for ClientSide and ServerSide are synchronized on the oc_os channel; this abstractly models the synchronization on port communication between the components in which the broker is not directly involved. This model allows the client side of any peer to connect to the server side of any peer (abstracting from the details of matching the peers).

The confirmCS and confirmSS messages model the confirmation sent back from the broker to the open session requests by the peers. In the implementation, this will be an implicit reply which is therefore not modeled in the behavioral interfaces of the peers in Section 2. These edges synchronize with the method implementations (explained next) in order to reduce the nondeterminism in the model.

Methods. The methods also use the invoke channel for sending messages. Fig. 7 shows the automata implementation of two methods for handling the openCS and register events. In openCS, and similarly in every method, the keyword **caller** refers to the object/component that has called this method. The scheduler should be able to start each method and be notified when the method finishes, so that it can start the next method. To this end, method automata start with a synchronization on the start channel, and finish with a transition synchronizing on the finish channel leading back to the initial location. The implementation of the openCS method involves sending a message confirmCS back to the sender, while the register method is modeled merely as a time delay.

3.3.1 Checking Schedulability

When an object is instantiated, an off-the-shelf scheduler is selected and (possibly) tailored to the particular needs of the object. For an object, we get a network of timed automata in UPPAAL by instantiating the automata templates for methods,

behavioral interface and the scheduler. There are two conditions indicating that a system is not schedulable:

(i) The scheduler receives a new message when the message queue is already full. In theory [11], a schedulable object needs a queue length of at most $\lceil d_{max}/b_{min} \rceil$, where d_{max} is the biggest deadline value used and b_{min} is the smallest execution time of all methods.

(ii) The deadline of at least one message in the queue is missed.

In either of the above cases, the scheduler automaton goes to a location called `Error`. This location has no outgoing transitions and therefore causes deadlock. Therefore, absence of deadlock implies schedulability, as well as correct output behavior for the object.

Due to the high amount of concurrency in the model, model checking is of limited use. Nevertheless, we can use the simulation feature of Uppaal [17] to analyze bigger systems. We measure the worst-case response time for each message, which identifies a lower bound for the deadline value in a schedulable system.

4 Conclusions

The *Credo* project has been successful in developing modeling and analysis techniques addressing highly reconfigurable distributed systems. In this paper, we described when and how to use these tools and techniques at the design stage of a software development process. At a high level of abstraction, the dynamic connections between the components are modeled using data-flow networks and verified, e.g., for absence of deadlock. Then an abstract object-oriented model of the implementation is devised in Creol, which has an executable formal semantics. This model is used for further analysis of functional as well as non-functional properties, e.g., schedulability. The conformance between the object-oriented and dataflow models as well as the conformance between an implementation in a programming language and the Creol model is tested.

The process described in this paper can be integrated in the existing software development methodologies which support component-based modeling, and thus enhance them with support for formal modeling and analysis of dynamically reconfigurable distributed systems. In the future, we intend to broaden the scope of the *Credo* modeling language and its corresponding tool suite in order to support the full development life-cycle of large-scale, open systems. This involves, on one hand, integrating models of software architecture into the process; and on the other hand, working further on deployment concerns such as scheduling.

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