SPIN-ning Software Architectures: A Method for Exploring Complex Systems

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Abstract

When designing complex systems that provide multiple non-functional properties, it is usual to try to reuse (and finally compose) simpler existing designs, which deal with each of these properties in solitude. This paper describes a method for automatically and quickly identifying all the different ways one can compose such designs, with the aid of a model checker.

Keywords: *architectural composition, architecture transformation, architecture discovery, architectural debugging.*

1. Introduction

Complex software systems need to provide multiple non-functional properties such as security, reliability, persistency, *etc.*. When designing and building them, it is only logical to try to reuse existing proven designs/solutions for each one of the requested properties [20]. In this way, one can gain both in completion time for a first version of the system and, more importantly, in maintenance efforts later on, since reusable components and general solutions for a particular property tend to be a lot more stable, and errors in them are found and corrected sooner than those built explicitly for a particular system.

This, in particular, is the reason for the growing interest in *component based software engineering* [4, 8, 29] and in *middleware* solutions [18, 22, 25, 26, 30, 31, 36]. Currently there exists quite a large set of reusable components, often referred to as middleware in the setting of distributed systems, and an equally large set of *architectural/design patterns*, *i.e.*, of architectures that use such reusable components in order to provide a particular property to an application.

Since no architectural pattern can be expected to provide all the different kinds of properties a real system requires, the designer must either create a new pattern from scratch or try to reuse existing ones and to compose them. Given the costs in developing a completely new pattern and components, and the benefits of reuse, it is only regrettable that designers have no available methods and tools for easing their task of composing different architectural patterns. Currently, one has to investigate different combinations of solutions, *e.g.*, $security\_solution_i$ with $reliability\_solution_j$, in order to find the ones that can best cooperate with each other. In addition, one has to explore the different ways of combining/composing a set of *particular* designs, since there is more than a single way to compose architectures, when these are indeed composable. This multitude of different ways to compose two patterns is due to the fact that middleware/reusable components have general enough interfaces, to allow for their reuse in as many different settings as possible. Thus, designers cannot sufficiently constrain the space of possible solutions by taking into account only the interfaces of the various components; not to mention the insufficiency of interfaces to communicate the correct ways one can use a component, see for example [5, 15]. To make things worse, even after having found a set of solutions that can indeed cooperate, one has to continue investigating combinations of other existing solutions as well, so as to find the set that optimizes other requirements, such as system throughput, cost of obtaining the required components, cost of training in-house developers at using them, *etc.*.

It becomes apparent that the designer is faced with a large number of different cases to be explored and assessed. The fact that currently no aid exists forces one to investigate very few of these cases. So, designers just try to make an educated guess of what a “good enough” solution would be. However, as is already well known from other areas, such as that of program optimization, solutions that at first seem as fast/small/“good” enough are not necessarily so and, even worse, they sometimes are found to have none of these properties when put under close scrutiny. Therefore, if one wants to obtain a truly good solution, the different possible solutions should be thoroughly investigated, in order to avoid common fallacies that lead to sub-optimal solutions.

In the following, we present a method for discovering all the possible *architectural configurations* with which different architectural patterns can be composed, *i.e.*, identify the particular bindings between the inputs and outputs of the components of a system, that allow the system to offer the properties of all the patterns used. Thus, we show how one can identify sets of existing solutions that can be used together, as well as, all the allowable patterns of use (configurations) for each particular set.

This method can also be used by the designer of a new architectural pattern or reusable component/middleware solution, to search for incompatibilities and insufficiencies by trying to compose with other already existing patterns. Thus, problems of architectural mismatch [15] can be identified and corrected early on in the design phase and the development of the specific components can later be based upon more mature models than usual. Since such architectural mismatches are the hardest ones to solve when building a system out of reusable components, we believe that this method can help ease (and increase) the application of component based software engineering.

The paper is divided into the following sections: Section 2 presents the proposed method for composing architectural patterns, Section 3 shows how it can be applied in a more concrete setting, Section 4 discusses some of the issues arising, while Section 5 makes a comparison with related work. Finally, we present our conclusions in Section 6.

2. A method for composing architectural patterns

When composing two architectural patterns, we have the following information available:

- the *generic* components, *i.e.*, those that a designer can substitute with components from the application that will make direct use of the pattern. In the patterns themselves, their behavior is left largely unspecified, usually acting just as sources and sinks of data.
- The *specific* components, *i.e.*, those specified in detail and which correspond to the reusable part of the pattern.
- The *architectural configuration*, *i.e.*, the bindings of input and output ports of the various components.

In order to maximize reuse, we refrain from altering either kind of components. Thus, the only part of the architectures that we can modify is their configurations, *i.e.*, try different bindings among the components to obtain a new pattern. This leads to a combinatorial algorithm: if there are N components in total, with each one having one input and one output port, then we would obtain $N!$ different patterns.

To guide us through this huge number of possible cases, we use the initial configurations as sources of constraints. That is, we only want to construct patterns where by removing all the components of the second pattern one would obtain the first pattern and vice versa. Thus the data-flows of the original architectures are preserved, *i.e.*, if a component $\mathcal{A}$ was directly sending a message to a component $\mathcal{B}$ in one of them, then such a communication link would also exist in the resulting compositions, possibly with some components of the other architecture being in the middle.

The patterns obtained in this manner do not necessarily provide the property the designer wishes to obtain. Therefore, one must still verify each one independently to find the ones that are indeed useful. The above can be easily automated with the use of a *model checker*. These are tools that can deal with vast search spaces and, in contrast to theorem provers, they can be used without requiring much user intervention/guidance. Their primary use is to identify *errors* in a model, *i.e.*, to expose series of events that can lead the modeled system in an undesired state, such as deadlock, message loss, out-of-order message reception, *etc.*. The undesired behavior/states are symbolically described by the user using some variant of Temporal Logic, such as a linear-time logic (Linear Temporal Logic - LTL) or a branching-time logic (Computational Tree Logic - CTL), see [10] for a comparison of them and [7] for more about model checking.

2.1. Composing with a modeling language

In order to automate the composition process, one has to change the models of the components so that they follow a certain set of rules. First, components should communicate through channels that they receive as arguments at run-time and are not hard-coded into their models, so that it is possible to change them at run-time while trying different configurations. These configurations are created by a new component, hereafter called the *Binder*; Table 1 shows the code for binding in a random manner. The code in Table 1 stores in the array `Inputs` a permutation of the indexes to the `channels` array. Then, we assume a specific ordering of the architectural elements (components/connectors), *e.g.*, that element $\mathcal{A}$ is element No. 1, $\mathcal{B}$ is No. 2, *etc.* *. We also assume an ordering of the input and output ports, *i.e.*, channels, of each element, so that we can refer to the ports of element $\mathcal{A}$ as input ports $I[1 \cdots n]$, and to those of $\mathcal{B}$ as $I[(n+1) \cdots (n+m)]$ (respectively for their output ports $O[1 \cdots k]$ and $O[(k+1) \cdots l]$),

*This ordering can be chosen randomly.

Table 1. Random binding of input and output ports in PROMELA

```
1  byte    Inputs[CHANNELS] ;
2  chan    channels[CHANNELS];
3  active proctype Binder()
4  {
5    int  i, target, UnCh, r ;
6    bit  channel_bound[CHANNELS]; /* Is channels[i] bound or not? */
7    run random_generator() ;      /* Start the random number generator. */
8    i = 1 ; UnCh = CHANNELS ;     /* UnCh holds the number of remaining unbound channels. */
9    do
10   :: (i <= CHANNELS) ->
11      /* Choose a random number between 1 and UnCh (inclusive). */
12      random_gen ! UnCh ;        /* Send the generator the upper limit. */
13      random_gen ? r ;           /* Receive a random number in [1,UnCh]. */
14      target = 0 ;               /* Find the r-th unbounded channel. */
15      do
16      :: (target <= CHANNELS) ->
17         if
18         :: (! channel_bound[target]) ->
19            if
20            :: (r > 1) -> r--
21            :: else    -> break /* Found it. */
22            fi
23         :: else -> skip
24         fi ;
25         target++
26      :: else -> break
27      od ;
28      if                         /* Ensure that r is indeed 1... */
29      :: ( 1 == r) -> skip
30      :: else      -> block_here()
31      fi ;
32      /* Input on port i, will be received from channel target; we mark it as bound. */
33      Inputs[i] = target ; channel_bound[target] = 1 ; printf("Inputs[%d] = %d\n", i, target) ;
34      UnCh-- ;                   /* We now have one less unbound channel. */
35      i++ ;
36   :: else -> break
37   od ;
38   ...
39 }
```

where n, m (respectively k, l) are the number of input (respectively output) ports of $\mathcal{A}$ and $\mathcal{B}$. Using these arrays, an element can then access its ports using the expression `channels[`O[element_id]`]` for its output ports and `channels[Inputs[`I[element_id]`]]` for its input ones. In other words, the i^{th} output port is always the i^{th} channel, while the i^{th} input port is chosen in a non-deterministic way[†]. Finally, after having completed the assignments of channels to input and output ports, the *Binder* proceeds with spawning the processes that correspond to the architectural elements, to verify the requested property.

As aforementioned, however, the number of configurations thus created is $N!$. Therefore, it is evident that we must constrain the possible combinations at this stage. Unfortunately, the modeling language of SPIN, PROMELA, does not allow us to easily express the full set of constraints we need. Therefore, we use a weaker set of constraints at this stage: when choosing among channels for an input port, we only consider channels corresponding to output ports of components that belong to the other architecture, or of components that were *directly* sending data to that input port in the initial architecture. The changes needed in the code of the *Binder* for this are minimal; it suffices to add an array of booleans, `channel_constrained[CHANNELS]`, which we use right after line 10 in Table 1 to mark, for the current input port, those output ports which are allowed to bind to it. We subsequently use it in line 18 to constrain the choice of channels, by changing the condition to `(! channel_bound[target]) && ! channel_constrained[target]`. Then, for enforcing the full constraints arising from the data-flows in the initial configurations, each component should add to messages it is sending, its signature, *i.e.*, a value identifying the particular component. It should also check that the signatures in the messages it is receiving are those of the components that "preceded" it in its initial architectural pattern and only those. In this way, if a component receives a message that has not passed through all the components that were supposed to treat it in its initial architecture, or that has passed from some component(s) that should not have treated it yet, then the signatures will be incorrect and so we can dismiss this as an invalid composition of the two configurations.

Finally, when composing architectural patterns $Arch_1$ with $Arch_2$ ($Arch_1 \oplus Arch_2$), we must take into consideration the cases where a component in $Arch_1$ has *multiple*

[†]The interested reader can find out more by visiting `html://www-rocq.inria.fr/~kloukina/Code/Spin/`.

outputs and thus multiple paths are formed after it. Then it may be the case that, for the composition to work, one needs to introduce components from $Arch_2$ in more than one of these paths, so that the property provided by the second pattern holds for all of them. To be able to do so we calculate the *degree of multiplicity* ($\Pi(\cdot)$) of $Arch_1$, *i.e.*, the sum of the number of outgoing connections, over the components of $Arch_1$ that have multiple outgoing connections, or 1 if all components have a single outgoing connection. Then, we provide the model checker with the components of $Arch_1$ and $\Pi(Arch_1)$ copies of the components of $Arch_2$. This allows us to have enough components of the second architecture available for placing them at the different paths. These copies are handled specially by the *Binder*, in the sense that they are the only ones allowed to receive input from themselves, effectively removing them from the rest of the system when they are not really needed.

When executing the model, the *Binder* will randomly pick a configuration and then start the rest of the components. When it starts a component it passes to it as arguments the channels from which it will receive input and those to which it will send output.

By asking a model checker to verify that the property required *never holds*, *i.e.*, $\neg \mathrm{E} \neg bound \wedge \bigcirc \mathrm{A}(bound \wedge \Box p)$ where p is the property we want our system to provide, we can force it to report to us the exact configurations (if any) for which it does indeed hold, that is, find a path (E) where, after ($\bigcirc$) having *bound* the components, p always holds ($\Box$) for all paths (A).

From the above discussion, it is evident that we are assuming an order among the architectures to be composed. This order is given by the user and is needed for two reasons: first, for knowing whether to consider $\Pi(Arch_1)$ copies of $Arch_2$ or vice-versa and, secondly and most importantly, for knowing that we will be using the generic components of $Arch_1$ and not those of $Arch_2$. This latter information is needed since we are constraining the bindings of the generic components as well, just as we are doing for the specific ones.

3. Experiment

In this section we describe how one can apply the composition method on two particular architectural patterns. These were chosen because of their relevance to middleware architectures. The first pattern provides secure communication between a client and a server by using pairs of encoders/decoders (hereafter referred to as *Encode-Decode* - see Fig. 1(a)). It is a classic example of a middleware architecture, effectively implementing a network stack just like a CORBA ORB does. The second architectural pattern provides reliability for an application server and a communication medium by replicating them and introducing a component that forks (multicasts) the client's requests to the server replicas over an unreliable medium and a component that merges the replicas' replies and returns a result to the client (hereafter referred to as *Fork-Merge* - see Fig. 1(b)). Even though this one deviates from the classic network stack paradigm, it is of particular importance to distributed systems, since their complexity is partially due to the possibility of communication/component faults. Additionally, it is a pattern whose configuration contains components with multiple outputs and thus allows us to test our method with a pattern whose degree of multiplicity is greater than one.

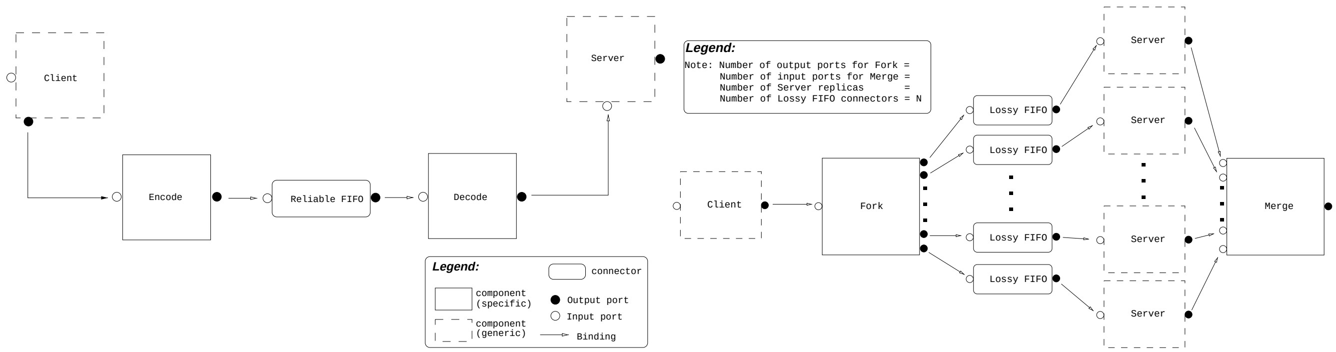
In the case of Fork-Merge, only Fork has multiple outgoing connections, so $\Pi(\text{Fork-Merge}) = N$, *i.e.*, the number of the Fork component's outgoing connections. In Encode-Decode no component has multiple outgoing connections, so its degree of multiplicity is equal to 1.

Both patterns were validated with respect to the property that all messages sent by the client are eventually received (and in the correct order) by the server (or at least by one of them in the case of Fork-Merge). This non-lossy, FIFO receipt of messages has different meanings for each one of the architectures; for Encode-Decode it means that the encoding of messages works correctly, while for Fork-Merge that the system is fault-tolerant (up to a certain number of faults).

The property that we want the composed patterns to provide is the conjunction of the two initial properties. Even though the wording of the property remains the same, its meaning now is that the system will be both secure (at some parts of it) and fault-tolerant (at some parts of it). To simplify the property and the model, we removed the clients and the servers altogether and replaced them with `Env_source` and `Env_sink`. The former provides a data stream to test the pattern against and the latter consumes the data stream at the end and checks the signatures of the messages to assure that all components of both architectural patterns have been used. This is the same as if we had left the clients and servers in the model and considered the `Env_source` and `Env_sink` processes as non-obstructive observers right after the client and right after the last component. Thus, the property becomes that all messages sent from `Env_source` will be eventually received (and in the correct order) by `Env_sink`. For this kind of property it suffices that messages can take three distinct values [2, 39], which allows us to validate the model without suffering from state explosion due to the infinitely possible values a message may take. So given the three different message types *white*, *red* and *blue*, the property p is:

$$\begin{array}{rl} & \Box(\mathrm{sent\_red} \;\Rightarrow\; \Diamond \mathrm{received\_red}) \\ \wedge & \neg(\neg \mathrm{received\_red}\, \mathcal{U}\, \mathrm{received\_blue}) \end{array} \tag{1}$$

where the first part demands no losses of messages and the



(a) Encode-Decode: A pattern for secure communication in a client-server system

(b) Fork-Merge: A pattern for augmenting the reliability of a server and a communication medium in a client-server system

Figure 1. Two software architectural patterns

second demands that blue messages are received after red ones which is the FIFO order, since they are emitted in that order.

The model checker we are using is SPIN [16, 17, 35] which was specifically developed for the verification of asynchronous models, as are the middleware architectures we are interested in; it is freely available and attracts interest from a large group of researchers. The particular features of SPIN that make it interesting for our method is its support of channels, its ability to report *all* the errors in a model and not just the first one, as well as the resemblance of its modeling language, PROMELA, to a programming language.

SPIN is used by providing a model of the system in PROMELA, as well as a formula in LTL that codifies erroneous behaviors of the system. Then it checks that the different behaviors/traces the model can produce do not belong to the erroneous ones.

Table 2 shows the model of the reliable FIFO connector component of the Encode-Decode architecture as it was used in this experiment. Lines 8–13 show the passing of input/output channels at run-time to the component and lines 20–31 and 33–38 the checking of signatures.

Both orderings for the composition of the architectures were considered in the experiment, *i.e.*, Fork-Merge $\oplus$ Encode-Decode as well as Encode-Decode $\oplus$ Fork-Merge.

Each composition was done in two phases. In the first, we used the *Binder* component to identify all different configurations of the available components and in the second we verified each one of those with respect to p (see property (1)) to obtain the solutions. The reason for which we did not verify the models against $\neg \mathrm{E} \neg bound \wedge \bigcirc \mathrm{A}(bound \wedge \Box p)$ but did a two step verification, is that SPIN does not support branching-time temporal formulæ. If we had tried to verify them against $\neg \Diamond(\neg bound \wedge \bigcirc(bound \wedge \Box p))$, then SPIN would have reported all the different traces for which p always holds for each configuration, which are infinitely many. Note, however, that a method was proposed in [38] for allowing SPIN to verify CTL* formulæ, which is a superset of both LTL and CTL.

In the first phase, we obtained 90 different configurations for Fork-Merge $\oplus$ Encode-Decode, down from $12! = 479001600$ [‡] which we would get if *Binder* did not use constraints. For Encode-Decode $\oplus$ Fork-Merge the initial $9! = 362880$ [§] configurations were reduced to just 28 in the first phase.

For the second phase, we remarked that while SPIN managed to reveal problems in configurations that are invalid quite quickly (usually in less than 3 seconds), it needed about 3 hours to validate the correct ones. Therefore, we first run SPIN on each of the configurations with a timeout of 1 minute and then collected the cases that had not finished and verified them all together, which thanks to SPIN's partial-order reduction took about the same time.

The 90 different configurations for Fork-Merge $\oplus$ Encode-Decode were obtained in less than 4 seconds. Using the 1 minute timeout, we retrieved 5 cases in 21 minutes which we subsequently verified in 3 hours and 10 minutes. The 28 configurations for Encode-Decode $\oplus$ Fork-Merge were obtained in less than 6 seconds. Then, we retrieved 4 cases in 8.5 minutes and verified them in 2 hours and 48 minutes. Thus, the time for obtaining 9 different solutions was 29.5 minutes and another 5 hours and 58 minutes were needed to fully verify them.

Some of the obtained solutions are shown in Fig. 2. Components of Encode-Decode are drawn using boxes, those of Fork-Merge using ellipses and `Env_source` and `Env_sink` using trapeziums. The `Encode_2` and `De-`

[‡] We have `Env_source`, `Env_sink`, N Encoders, N Decoders, N reliable Connectors, 2 lossy Connectors, Fork and Merge, for a total of 12 components, when $N = 2$ as was the case in this experiment.

[§] We have `Env_source`, `Env_sink`, an Encoder, a Decoder, a reliable Connector, 2 lossy Connectors, Fork and Merge, for a total of 9 components.

Table 2. A reliable FIFO connector modeled in Promela

```
/* Reliable / FIFO / No duplicates / No spurious messages connector. */
proctype ConnectorR(byte id)
{
  Msg  cR_current_message ;
  byte MyInChannel ;
  byte MyOutChannel ;

  /* Use your id to assign the input and output channels.
     Note: the Inputs/inputs/outputs arrays have been properly set up by the Binder. */
  d_step {
     MyInChannel = Inputs[inputs[id]] ;
     MyOutChannel = outputs[id] ;
  } ;

  do
  :: true ->                                        /* Repeat this forever. */
     d_step {
        channels[MyInChannel] ? cR_current_message ;     /* Receive a message. */

#ifdef  WITH_SIGNATURES
        /* Check the message's signature. */
        if
        :: (   cR_current_message.ed_encoded_p[0]        /* Must be signed by Encode. */
           && !cR_current_message.ed_CR_p     [0]        /* Must *not* be signed by me. */
           && !cR_current_message.ed_decoded_p[0]) ->    /* Must *not* be signed by Decode. */
           cR_current_message.ed_CR_p[0] = 1             /* OK, I'm signing it. */
        :: else ->                                       /* Incorrect signatures... */
           printf("MSC: ConnectorR[%d]: I'm blocking\n", id) ;
           block_p = 1                                   /* Force an error later on. */
        fi ;
#endif
     } ;
#ifdef  WITH_SIGNATURES
     if
     :: block_p -> assert(0)                             /* Signal the error here and stop. */
     :: else    -> skip
     fi ;
#endif

     channels[MyOutChannel] ! cR_current_message         /* Send a message. */
  od
}
```

`code_2` components in Fig. 2(b) are shown short-wired because they are not really supposed to be used by the architecture; these are the second copies of the `Encode` and `Decode` components due to Fork-Merge's degree of multiplicity which throughout the experiment was assumed to be 2.

We should note here that for larger architectural patterns than the two used in this experiment, a model checker may be unable to cover all the candidate configurations in phase one of this method. One solution to this problem is to add additional pseudo-constraints for some components. That is, assume that component c_i cannot receive input from components c_j, c_k and in subsequent runs change these constraints, *i.e.*, allow it to receive input from c_j, c_k but disallow it to receive input from c_l, c_m, where all j, k, l, m are different.

4. Discussion

The configurations obtained from the first phase could be diminished even further, if we could use the whole initial connection graphs to constrain the configurations obtained, by insisting that a component has before it in a path all the components it had in its initial architecture and in the correct order. However, this is not easy to program using PROMELA. That is why we chose to use a weaker set of constraints, which allow the creation of some completely strange and obviously wrong configurations, *e.g.*, see Fig. 3.

In parallel to this work, we are working on a method which uses the initial connection graphs to create the different configurations that are then verified with SPIN [21], thus removing SPIN from phase one of this architectural identification method. By using all the structural information contained in the initial configurations, we are trying to create candidate configurations that already adhere to all of the constraints discussed so far. This would allow us to remove the current first phase and to dispense with the imposed constraints altogether, those of the first phase evidently, as well as those in the form of signatures. Thus the state space of the models would be reduced and the verification of the candidate configurations with respect to the required property would be sped up even further.

When trying to compose two different architectures, one may stumble upon the problem of having the two architectures expressed at very different abstraction levels, possibly using more than one abstraction techniques. Then, there is

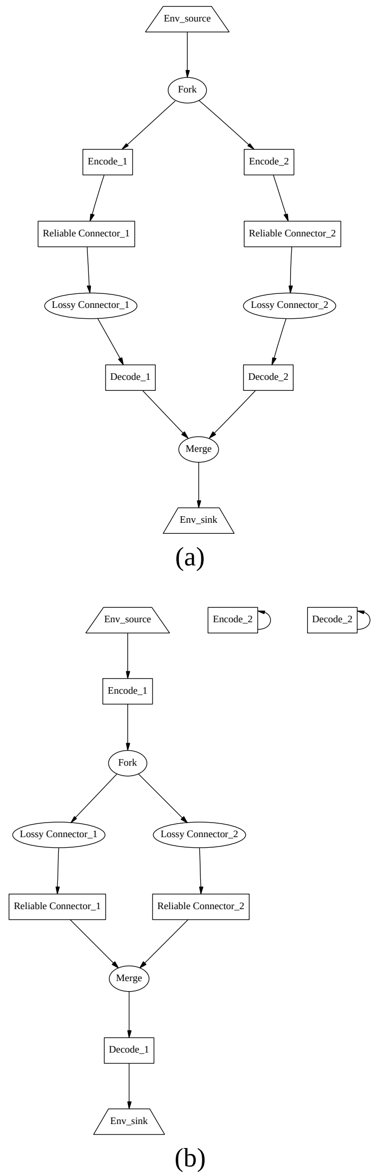


Figure 2. Two of the solutions for Fork-Merge $\oplus$ Encode-Decode

also the question of how to merge the different data structures used by the initial architectures to obtain data structures that can be used by a combined architecture.

In this experiment, both architectures used the same abstraction technique to map the possibly infinite values of a message to just three distinct values, which made it possible to easily verify the FIFO reception of data without suffering from state explosion.

As far as the data structures are concerned, we were able to just glue them together, thus having messages where one part of them was processed only from components of the Encode-Decode architecture, while the other was processed

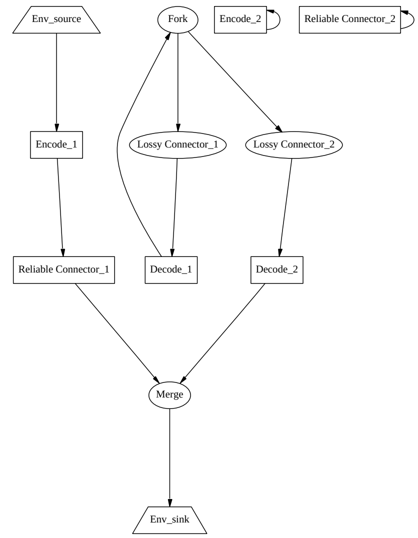


Figure 3. One of the (wrong) configurations obtained from phase one

by Fork-Merge's components. This was the reason (plus the rather naïve model of Merge) why we obtained solutions like the one shown in Fig. 2(b) where Merge (and the fictitious Servers before it) are assumed to be processing encoded messages (the decoding of these is done just after the merging of the Servers' replies). Even though the validity of such a solution can be defended theoretically, see for example [1] for a discussion of processing encoded data, it is something rarely expected to be seen in practice and a sign that the model(s) of some component(s) does not closely reflect reality.

It is therefore quite possible that one would have to do a considerable amount of work in order to bring both initial architectures at the same level of abstraction before composing them. The resulting state space might, however, be substantially big for a tool to check it all; automatic model abstraction [6, 14, 33, 37] and/or model slicing [27] may prove to be quite helpful in that case.

However, in the case of middleware architectures such as those proposed by the CORBA Services [30, 31], we expect the models of the different architectures to be using a rather common set of abstractions, making them easier to compose. In fact, we believe that the (possible FIFO) eventual reception of data suffices as a validation property for most of the middleware architectural patterns. Indeed, in the aforementioned experiment, Fork-Merge used this property to express that the pattern provided reliable communication, while Encode-Decode used the same property for expressing secure communication.

We believe that for particular domains, such as middleware services, it is possible to define a single kind of message types and a small set of properties one should verify, thus causing the models of the components of these patterns to be at equivalent abstraction levels.

Finally, we should mention that this method could also be used for creating more reusable architectures. This can be achieved by trying to compose an architecture with existing, more or less standard, architectures. Then, by studying the possible solutions obtained and even more importantly, the expected but not obtained solutions, one can identify the particular points of the architecture that caused these incompatibilities and correct the architecture early on in the design phase, before even having started to implement its components. This way one can avoid unpleasant surprises having to do with incompatible components and communication protocols. In the example mentioned, one would thus be incited to rework the models of the components so as to disallow results such as the one shown in Fig. 2(b).

5. Related work

To the best of our knowledge, the computation of composite configurations has not been examined in the past. Related work is mainly concerned with the composition of software systems at the specification level, hence leaving few opportunities for automating the process. The work that is the most related to ours is [28]. There, two complementary kinds of composition were identified: *vertical* and *horizontal*. The former relates to the top-down refinement process. Horizontal composition is used to compose instances of architectures to form one large composite architecture. It is handled by the developer on a case-by-case basis according to a simple syntactic criterion, *e.g.*, the composed architectures can share only components.

From the perspective of identifying a middleware configuration meeting application requirements, vertical composition serves refining those requirements into a concrete middleware configuration. This is the approach that is actually used in the Aster project [3] for promoting *design* and *software reuse* by allowing the systematic construction of customized middleware systems that are shown to match an application's nonfunctional requirements. However, vertical composition falls short when applications require different types of non-functional properties, as already suggested by the case-by-case approach to horizontal composition proposed by Moriconi *et al.*.

In the work appertained to software development processes, one finds multiple *architectural views* of software systems, each one addressing a concern of one of the various stake-holders (*e.g.*, end-users, managers, developers). In this direction, we find the work of [23] that introduces the "4+1" views of a software system architecture. The four system views (logical, process, development and physical) are then loosely linked together through use-case scenarios (*i.e.*, the "+1" view). Multiple-view descriptions of a software system were also considered in [12, 13]. This area of research work relates to ours in that it is concerned with the decomposition of the system's software specification in terms of various architectural views. However, the architectural views we consider are at a higher level of design, and all relate to the middleware architectural styles underlying the execution of distributed applications. Specifically, the software system "views" we focus on prescribe the middleware configurations to be used for enforcing given types of non-functional properties, which is to be composed with similar "views". In general, our work is complementary to the above references in that it offers methods and tools for helping the designer in reusing existing middleware platforms for the design of a software system complying with the architectural views that are set up during the design phase and that integrates non-functional considerations (*e.g.*, the process and physical views in the "4+1" views approach).

Composing components offering various properties (or *features*) has also been investigated in [40] for the specific case of telecommunication applications, where components can be assembled according to the *pipe-and-filter* architectural style. Even though features are usually self-contained and independent from the others, inconsistencies do arise and these are left to be resolved by the developer. Our context, however, is broader and cannot be reduced to simple horizontal compositions chaining middleware configurations. In fact, pipe and filter compositions rarely appear to be middleware compositions of much interest.

Finally, we should mention [24] where the authors discuss the *unification of architectural fragments*. In contrast to our method, they are able to unify similar components between different architectures, even when these are partially defined. However, in the kind of patterns we are considering, *i.e.*, fully described reusable-specific components plus partially defined generic components (called real components/placeholders respectively in that work), it is unclear whether they can obtain similar results, *i.e.*, different interweavings of the components of the two architectures.

6. Conclusions

Designing complex systems demands the use of many kinds of architectural patterns in order to provide the multiple non-functional properties these systems require. These different architectural patterns cannot be used in isolation but must be composed together and collaborate.

In this paper we have presented a method that constructs all possible combinations of two (or more) architectures, given the models of their components. Results can be obtained quite quickly, when the models are in the same level of abstraction. For example, we showed how one can apply it to automatically obtain all possible compositions of two architectures in less than 30 minutes.

In addition, it can be used to early debug and guide the architecture development process of highly reusable component solutions that are to be used along with already existing middleware solutions.

We are currently working on substituting the process of identifying candidate solutions (which we later on verify to ascertain that they indeed provide the requested properties) by a graph-based algorithm that fully utilizes the structural information of the architectures that we want to compose, *i.e.*, their configurations, so that we can substitute the rather naïve combinatorial method used now. That would highly reduce the cases passed on to verification and speed up the verification itself since now we could dispense with the signatures on the messages currently needed to discard cases. It would also highlight some cases where the models of the components do not allow a certain utilization, even though it is meaningful from a structural point of view, which may sometimes be a reason to revise the models themselves.

Acknowledgments: This work is partially funded by the IST DSoS ¶ research project. The authors would also like to acknowledge the help provided by Dr. Apostolos Zarras and the anonymous reviewers at WICSA2001 through their criticism and suggestions for improvement.

Figures 2 and 3 were created by the tool Dot from AT&T Labs' Graphviz package‖.

¶DSoS project home page: `http://www.newcastle.research.ec.org/dsos`

‖Graphviz's home page: `http://www.research.att.com/sw/tools/graphviz/`

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