

# TOWARD A FORMAL SEMANTICS FOR AUTONOMIC COMPONENTS

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**Abstract** Autonomic management can improve the QoS provided by parallel/distributed applications. Within the CoreGRID Component Model, the autonomic management is tailored to the automatic – monitoring-driven – alteration of the component assembly and, therefore, is defined as the effect of (distributed) management code.

This work yields a semantics based on *hypergraph* rewriting suitable to model the dynamic evolution and non-functional aspects of Service Oriented Architectures and component-based autonomic applications. In this regard, our main goal is to provide a formal description of adaptation operations that are typically only informally specified. We contend that our approach makes easier to raise the level of abstraction of management code in autonomic and adaptive applications.

## 1. Introduction

Developers of grid applications cannot rely neither on fixed target platforms nor on stability of their status [9]. This makes dynamic adaptivity of applications an essential feature in order to achieve user-defined levels of Quality of Service (QoS). In this regard, component technology has gained increased impetus in the grid community for its ability to provide a clear separation of concerns between application logic and QoS-driven adaptation, which can also be achieved *autonomically*. As an example, GCM (the Grid Component Model defined within the CoreGRID NoE) is a hierarchical component model explicitly designed to support component-based autonomic applications in highly dynamic and heterogeneous distributed platforms [4].

An assembly of components may be naturally modeled as a graph and, if components are autonomic, the graph can vary along with the program execution and may change according to input data and/or grid hardware status. These changes can be encoded as reaction rules within the component *Autonomic Manager* (hereafter denoted as *AM*). A proper encoding of these rules effectively realises the management policy, which can be specific of a given assembly or pre-defined for parametric assemblies (such as *behavioural skeletons*) [1–2]. In any case, the management plan relies on the reconfiguration operation exposed by the component model run-time support.

A major weakness of current component models (including GCM) is that the semantics of these operations are informally specified, thus making hard to reason about QoS-related management of components. In this work

- We discuss few primitives useful for component adaptation; the chosen operations are able to capture typical adaptation patterns in parallel/distributed application on top of the grid. These are presented as *non-functional interfaces* of components that trigger component assembly adaptation.
- We detail a semantics for these operations based on *hypergraph* rewriting suitable for the description of component concurrent semantics and assembly evolution along adaptations.

The key idea of our semantical model consists in modeling component-based applications by means of *hypergraphs* which generalise usual graphs by allowing *hyperedges*, namely arcs that can connect more than two nodes. Intuitively, hyperedges represent components able to interact through *ports* represented by nodes of hypergraphs. The *Synchronized Hyperedge Replacement* (SHR) model specifies how hypergraphs are rewritten according to a set of *productions*. Basically, rewritings represent adaptation of applications possibly triggered by the underlying grid middleware events (or by the applications themselves).

SHR has been shown suitable for modelling non-functional aspects of service oriented computing [6–7] and is one of the modelling and theoretical tools of the SENSORIA project [14]. For simplicity, we consider a simplified version of SHR where node fusions is limited and restriction is not considered. Even if, for the sake of simpleness, the SHR framework used in this work is not the most general available, it is sufficient to give semantics to the management primitives (aka adaptation operations) addressed here. The autonomic manager – by way of these adaptation operations – can structurally reconfigure an application to pursue the (statically or dynamically specified) user intentions in terms of QoS.

## 2. Autonomic Components and GCM

Autonomic systems enables dynamically defined adaptation by allowing adaptations, in the form of code, scripts or rules, to be added, removed or

modified at run-time. These systems typically rely on a clear separation of concerns between adaptation and application logic [10]. An autonomic component will typically consist of one or more managed components coupled with a single autonomic manager that controls them. To pursue its goal, the manager may trigger an adaptation of the managed components to react to a run-time change of application QoS requirements or to the platform status. In this regard, an assembly of self-managed components implements, via their managers, a distributed algorithm that manages the entire application.

The idea of autonomic management of parallel/distributed/grid applications is present in several programming frameworks, although in different flavours: ASSIST [15, 2], AutoMate [13], SAFRAN [5], and GCM [4] all include autonomic management features. The latter two are derived from a common ancestor, i.e. the Fractal hierarchical component model [12]. All the named frameworks, except SAFRAN, are targeted to distributed applications on grids.

GCM builds on the Fractal component model [12] and exhibits three prominent features: hierarchical composition, collective interactions and autonomic management. GCM components have two kinds of interfaces: functional and non-functional ones. The functional interfaces host all those ports concerned with implementation of the functional features of the component. The non-functional interfaces host all those ports needed to support the component management activity in the implementation of the non-functional features, i.e. all those features contributing to the efficiency of the component in obtaining the expected (functional) results but not directly involved in result computation. Each GCM component therefore contains an *AM*, interacting with other managers in other components via the component non-functional interfaces. The *AM* implements the autonomic cycle via a simple program based on reactive rules. These rules are typically specified as a collection of *when-event-if-cond-then-adapt.op* clauses, where *event* is raised by the monitoring of component internal or external activity (e.g. the component server interface received a request, and the platform running a component exceeded a threshold load, respectively); *cond* is an expression over component internal attributes (e.g. component life-cycle status); *adapt.op* represents an adaptation operation (e.g. create, destroy a component, wire, unwire components, notify events to another component's manager) [5].

We informally describe some common adaptation operations that may be assigned to configuration interfaces are the following:

**Migration** A component is required to change its running location (e.g. platform, site). The request must include the new location and can be performed while keeping its attached external state (*go*) or restating from a fresh default state (*start*).

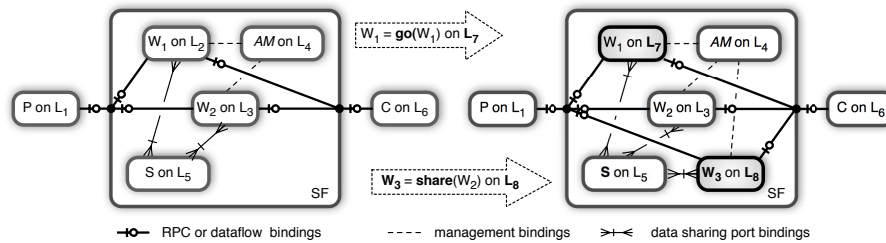
**Replication** A component (either composite or primitive) is replicated. Replication operation is particularly targeted to composite components exhibit-

ing the parametric replication of inner components (such as behaviour skeletons), and can be used to change their parallelism degree (and thus their performance and fault-tolerance properties). Replication events are further characterized with respect to their relation with replicated component state, if any. A component replica may be created with a fresh external state, carry a copy of the external state (**copy**), or share the external state with the source component (**share**).

**Kill** A component is killed. Due to this kind of action disconnected components (and in particular storage managers) can subject to garbage collection.

Described primitives make possible the implementation of several adaptation paradigms. In particular, migration may be used to adapt the application to changes of grid topology as well as to performance drop of resources. Replication and kill may be used to adapt both data and task parallel computation. In particular, replication with share enables the redistribution of sub-task in data parallel computations; replication with copy enables hot-redundancy. Both stateful and stateless farm computation (parameter-sweeping, embarrassingly parallel) may be reshaped both in parallelism degree and location run by using replication and kill.

EXAMPLE 1 Let  $P, C, SF, S, AM, W_1, W_2, W_3$  components (Producer, Consumer, Stateful Farm<sup>1</sup>, Storage, Autonomic Manager, and Workers);  $L_1 \cdots L_8$  locations. These kinds of bindings are used in the assembly (see also Sec. 4).



The described assembly of components (left) is paradigmatic of many producer-filter-consumer applications, where the producer ( $P$ ) generates a stream of data and the filter is parallel component ( $SF$ ) exhibiting a shared state among its inner components (e.g. a database). The original assembly (left) can be dynamically adapted (right) by way of two adaptation operations to react to run-time events, such as a request of increasing the throughput. The **go** operation moves  $W_1$  from  $L_2$  to  $L_7$  (as an example to move a component onto a more powerful machine); the **share** operation that replicates  $W_2$  and place it in the new location  $L_8$  (to increase the parallelism degree). Both operations preserve the

<sup>1</sup>This component is a composite component, and in particular it is an instance of a behavioural skeleton [1].

external state of the migrated/replicated component, which is realised by way of a storage component) attached via a data sharing interface [3].

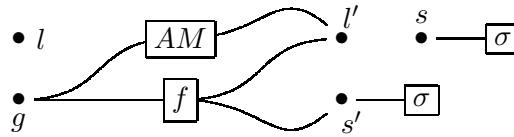
Example 1 illustrates how the management can be described from a *global viewpoint*. Indeed, the system is described by in a rather detailed way, e.g., components are explicitly enumerated along with their connections. Even if this global viewpoint is useful (and sometime unavoidable) when designing distributed systems, it falls short in describing what single components are supposed to do when a reconfiguration is required. In other terms, it is hard to tell what the *local* behaviour of each component should be in order to obtain the reconfiguration described by the *global* view.

Also, it is worth remarking that, though the diagram clearly describes the changes triggered by *AM* in this scenario, the lack of a formal semantics leaves some ambiguities. For example, it is not clear if the reconfiguration should take place if, and only if, the system is configured as on the lhs or this is rather a "template" configuration (e.g., should the system reconfigure itself also when  $W_2$  is connected to  $W_1$  rather than to  $D$ ? What if  $W_2$  was not present?). Of course, such ambiguous situations can be avoided when a formal semantics is adopted.

### 3. A Walk through SHR

*Synchronised Hyperedge Replacement* (SHR) can be thought of as a rule-based framework for modelling (various aspects of) of distributed computing [7] modelled as *hypergraphs*, a generalisation of graphs roughly representing (sets of) relations among nodes. While graphs represent (sets of) binary relations (labelled arcs connect exactly two nodes), labelled *hyperedges* (hereafter, edges) can connect any number of nodes. We give an informal albeit precise description of *hypergraphs* and SHR through a suitable graphical notation. The interested reader is referred to [7, 11] and references therein for the technical details.

EXAMPLE 2 *In our graphical notation, a hypergraph is depicted as*

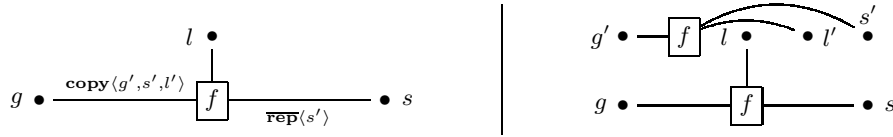


Edges (labelled by  $f$ ,  $AM$  and  $\sigma$ ) are connected to nodes ( $g$ ,  $l$ ,  $l'$ ,  $s$  and  $s'$ ). Specifically,  $AM$  connects  $g$  and  $l'$ ,  $f$  connects  $g$ ,  $l'$  and  $s'$  while two  $\sigma$ -labelled edges are attached to  $s$  and  $s'$ . Notice that nodes can be isolated (e.g.,  $l$ ).

Hyperedges represent (distributed) components that interact through *ports* represented by nodes. Connections between edges and nodes, called *tentacles*, allow components sharing ports to interact (e.g., in Example 2,  $f$  and  $AM$  can interact on  $g$  and on  $l'$ ).

EXAMPLE 3 *The hypergraph in Example 2 represents (part of) a system where a manager AM and a component  $f$  are located at  $l'$  and can interact on port  $g$ . The component  $f$  has access to the store at  $s'$  (e.g. by way of a data port [3]). In the system are also present another location  $l$  and store  $s$ .*

As in string grammars, SHR rewriting is driven by *productions*. In fact, strings can be rewritten according to a set of *productions*, i.e. rules of the form  $\alpha \rightarrow \beta$ , where  $\alpha$  and  $\beta$  are strings (over fixed alphabets of terminal and non-terminal symbols). Similarly, in SHR hypergraph rewritings are specified by productions of the form  $L \rightarrow R$ , where the lhs  $L$  is a hyperedge, the rhs  $R$  is a hypergraphs and states that occurrences of  $L$  can be replaced with  $R$ . Intuitively, edges correspond to non-terminals and can be replaced with a hypergraph according to their productions. In SHR, hypergraphs are rewritten by *synchronising* productions, namely edge replacement is *synchronised*: to apply the productions of edges sharing nodes, some conditions must be fulfilled. More precisely, an SHR production can be represented as follows:



where on the lhs is a decorated edge and on the rhs a hypergraph. The production above should be read as a rewriting rule specifying that edge  $f$  on the lhs can be replaced with the hypergraph on the rhs provided that the conditions on the tentacles are fulfilled. More precisely, **copy** and **rep** must be satisfied on node  $g$  and  $s$ , respectively while  $f$  is *idle* on node  $l$ , namely it does not pose any condition on  $l$ . According to our interpretation, this amounts to say that when component  $f$  is said to replicate with copy by its AM (condition **copy** on node  $g$ ), it tells its store to duplicate itself (condition **rep** on node  $s$ ). When such conditions are fulfilled, edge  $f$  is replaced with the hypergraph on the rhs which yield two instances of  $f$  one of which connected to the communicated nodes as prescribed by the rhs of the production. Indeed,  $f$  exposes three nodes on condition **copy** and one on **rep**; these represent nodes that are communicated (i.e.,  $g$  and  $l$  are node communication accounts for mobility as edges can dynamically detach their tentacles from nodes and connect them elsewhere).

SHR has a declarative flavour because programmers specify synchronization conditions of components independently from each other. Once the system is built (by opportunely connecting its components) it will evolve according to the possible synchronizations of the edges. Global transitions are obtained by

parallel application of productions with “compatible” conditions where compatibility depends on the chosen synchronisation policy<sup>2</sup>.

#### 4. Productions for Non-functional Interfaces

SHR can adequately formalise the non-functional interface mechanisms informally described in Sec. 2. Three conceptually distinct interfaces can be considered: *i*) interfaces between components and *AM* (for management bindings), *ii*) interfaces toward the external state (for data sharing bindings), and *iii*) interfaces for communicating with other components (for RPC/dataflow bindings). Since interfaces *iii* are application dependent, we focus on the coordination-related interfaces *i* and *ii*.

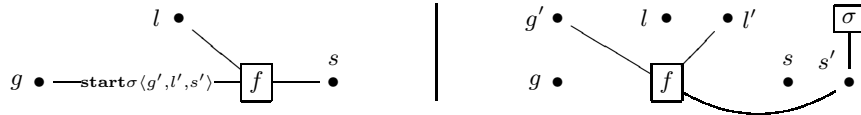
A main advantage of our approach is that all aspects of non-functional interfaces are captured in a uniform framework based on SHR. Indeed,

- components are abstracted as edges connected to form a hypergraph;
- the coordination interface of each component is separately declared and is not mingled with its computational activity;
- being SHR a *local* rewriting mechanism, it is possible to specify confined re-configuration of systems triggered by *local* conditions;

**Migration.** The migration of a component  $f$  is triggered when its *AM* raises a signal `go` with the new location on node  $g$ . The synchronisation of  $f$  on the `go` signal is given by following production:

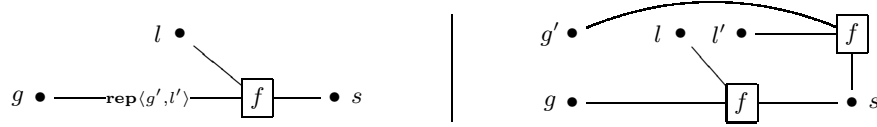


specifying that  $f$  running at  $l$  accepts to migrate to  $l'$  (lhs); the “location” tentacle of  $f$  is disconnected from  $l$  and attached to  $l'$  (rhs). Notice that  $f$  maintains the connection to the previous state  $s$  and  $l$  is still present. The tentacle connected to  $g$  on the lhs is connected to  $g'$  on the rhs; however, it might well be that  $g' = g$  ( $f$  is still connected to the original *AM*) or  $g \neq g'$  ( $f$  changes manager). Similarly, `start` moves the component to a new location  $l'$ . However, a new external state  $\sigma$  is created together with its attaching node:



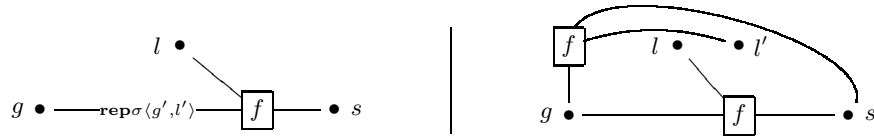
<sup>2</sup>SHR is parametric with respect to the synchronisation mechanism adopted and can even encompass several synchronisation mechanisms [7, 11].

**Replication.** Unlike migration, replication of  $f$  preserves its location:



the effect of the above production is to add a new instance of  $f$  at  $l'$  with  $AM$  connected to  $g'$ ; of course,  $l = l'$  and  $g = g'$  are possible. The newly generated instance shares external state with the original one.

Replication can also activate the new instance with a different state:

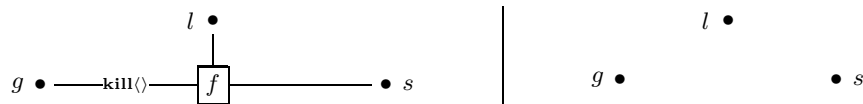


The production above creates a fresh replica of  $f$  at  $l'$  and assigns to it the manager at  $g'$ ; notice that the two instances of  $f$  share the state  $s$ .

Replication can also trigger a new instance of  $f$  that acts on a copy of the state original state as described in the production of page 6 where  $f$  must notify to its state to duplicate itself and connect the new copy on  $s'$ . Hence, the state connected to  $s$  duplicate itself on the node  $s'$  when the action complementary to  $\overline{\text{rep}}$  is received, as stated below.



**Component killing.** Components are killed using the following production:



stating that  $f$  disappears when its corresponding  $AM$  sends a **kill** signal.

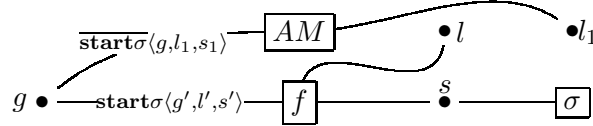
## 5. Synchronizing productions

The operational semantics of SHR is illustrated through an example that highlights the following steps:

- 1 individuate the adjacent tentacles labeled by compatible conditions;
- 2 determine the synchronizing productions and replace the (instances of) edges on their lhs with the hypergraphs on their rhs;
- 3 fuse the nodes that are equated by the synchronizations.

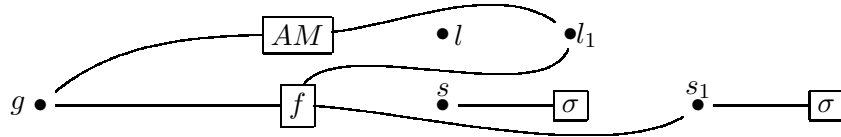
Let us apply the previous steps to show how migration works in a situation represented by the following hypergraph





where component  $f$  is running at  $l$  and shares  $g$  with a manager  $AM$  located at  $l_1$ . For brevity, tentacles are decorated with the conditions triggering the rewriting (step 1). Indeed, the tentacles of  $AM$  and of  $f$  incident on node  $g$  yield compatible output and input conditions respectively so that  $AM$  orders  $f$  to migrate to  $l_1$  and to use the store at  $s_1$  while staying connected to  $g$ .

Productions synchronisation consists in replacing the occurrences of the edges on the lhs with the hypergraphs specified in the rhs of the productions and applying the node fusions obtained by the node communicated. For instance, in the previous example the synchronising productions are the  $\text{start}\sigma$  production of  $f$  given in Sec. 4 and the production of  $AM$  whose lhs and rhs consist of  $AM$  connected to  $g$  and  $l_1$  (step 2). Hence, after the synchronization, the node fusions  $g' = g$ ,  $l' = l_1$  and  $s' = s_1$  are applied (step 3), so that the hypergraph is rewritten as



Let us remark that  $l$ ,  $\sigma$  and  $s$  remains in the final hypergraph. In fact they should not be removed because other edges can be allocated on  $l$  or access  $\sigma$ .

The intuitive description of SHR given in this section suggests the following design style and execution style:

- assign an edge to each component and specify their productions;
- represent the system as a hypergraph;
- decorate the tentacles with the synchronisation conditions;
- synchronize the productions until possible.

It is worth remarking that, unlike other semantical frameworks (e.g., process calculi), in SHR synchronisation conditions may require more than two (productions of) components to be synchronised. This actually depends on the synchronisation policy at hand. For instance, in the migration rewriting described in this section, it is possible to use broadcast interactions on the node  $g$  so that *all* the components connected on  $g$  will move at  $l'$  when the productions are synchronised.

## 6. Conclusions

SHR is one of the modelling and theoretical frameworks of the SENSORIA project [14] and has been exploited in [6] for managing application level *service*

*level agreement* (SLA) in a distributed environment; in [7] several variants of SHR have been described in a uniform context showing how this formalism can suitably tackle many programming and modelling facets arising in service oriented computing. In this paper we have shown how SHR can be suitably used to formalise both adaption operations and the evolution of component-based autonomic applications.

In an autonomic component model, as GCM, the *AM* relies on adaptation operation to realise its management policy (during the *execution* phase of the autonomic cycle). In general, a proper formalisation of adaptation operations (possibly involving the *AM* itself), may help in

- developing correct and effective management policies providing the developer with a precise description of the effect (semantics) adaption operations;
- formally proving the proprieties of a single adaptations or sequences of them;
- formally proving local or global invariants characterising the evolution of assemblies of autonomic components;
- guiding developers of the component model itself to establish the effectiveness of provided adaptation operations (e.g. the completeness of the set of operations with respect to a given planned evolution of the assembly).

This work covers the first of these items, thus represents a first step in this roadmap, whereas successive items can be enumerated in the future work. The presented adaptation operations are currently implemented in the reference implementation of GCM (developed within the GridCOMP STREP project [8]); their effectiveness in managing the QoS of grid applications is reported in [1].

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