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Communicating Concurrent Objects in HiddenCCS

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Abstract

In this paper we add value-passing communication to hiddenCCS, a new formalism proposed in [[2](#_bookmark5)] for synchronizing concurrent objects. We use hidden algebra to specify object-oriented systems, and CCS process algebra to describe the coordination aspects. The new specification formalism extends the object specification with synchronization and communication elements associated with methods and attributes of the objects, and use a CCS description of the interaction patterns. The operational semantics of hiddenCCS specifications is based on labeled transition systems which can be specified in rewriting logic. We use Maude as a platform for verification of the communicating concurrent objects specified in hiddenCCS. Triple Modular Redundancy is used as an example of a hiddenCCS specification and its verification in Maude.

*Keywords:* Algebraic specification, concurrent systems, process algebra, object- oriented specification, hidden algebra, rewriting logic, Maude, CCS, linear temporal logic, verification techniques.

# Introduction

The motivating idea of this paper is to study the coordination of some local goals given by various computing components in a concurrent system. In our approach, hidden algebra is used to specify the local goals as concurrent objects, and CCS is used to describe the coordination of the synchronizing and communicating objects.

State-based formalisms such as hidden algebra provide specification tech- niques for capturing complex data and states; however they are weak for capturing the interaction aspects of communicating concurrent systems. On the other hand, the process algebra and other concurrent calculi can support

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dynamic interaction and mobility; however they generally are not adequate to model data and states of complex concurrent systems. We have proposed an integration of hidden algebra and CCS, introducing hiddenCCS in [[2](#_bookmark5)]. In hid- denCCS we use hidden algebra to specify objects, and CCS to describe their synchronization. In this paper we extend the hiddenCCS approach, adding value-passing communication between distributed objects. We keep the name hiddenCCS for this extension. Synchronization and communication are pre- sented as two forms of interaction between objects. From an object-oriented point of view, we preserve the properties and the expressive power of hidden algebra specification; from a process algebra point of view, we describe the possible patterns of interaction and preserve the expressive power of CCS.

Hidden algebra takes as basic the notion of equational behavioral satisfac- tion: this means that hidden specifications characterize how objects behave in response to a given set of experiments. Hidden algebra is able to handle several features of large systems, including local states, nondeterminism, as well as the usual features of the object-oriented programming paradigm [[8](#_bookmark9)]. CCS is a concurrency calculus used to model the interaction among objects; a CCS process expresses the capability of the system to interact with other systems running concurrently. We use CCS to specify the communication requirements, describing interaction patterns between concurrent objects.

We extend the algebraic specifications of hidden algebra with two ele- ments of interaction, namely with synchronization and communication ele- ments. Synchronization elements link two objects whenever one is asking for a resource, and the other can offer such a resource. Communication given by a method accessing an attribute is similar to a value-passing interaction from the object having the attribute to the object having the method. The formal operational semantics of hiddenCCS integrates model semantics of hid- den algebra and CCS reduction rules by using these elements of interaction. The resulting labeled transition systems are translated into rewriting logic specifications using the Maude implementations of CCS and Hennessy-Milner logic. We use the Maude implementation of the linear temporal logic to verify properties of the hiddenCCS specifications.

The structure of the paper is as follows. Section 2 briefly presents hidden algebra. Section 3 briefly presents CCS. Section 4 includes the main contribu- tions: we introduce the new hiddenCCS specifications, and present some theo- retical results. Then we show how the operational semantics of the hiddenCCS specifications is described in rewriting logic and how the Maude system is used to verify temporal properties of hiddenCCS specifications. Conclusions and references end the paper.

# Specification of Objects in Hidden Algebra

We briefly present the main concepts and notations of the hidden algebra. A detailed presentation of hidden algebra can be found in [[8](#_bookmark9),[14](#_bookmark14)].

A *ﬁxed data hidden-signature* Σ consists of:

* + two disjoint sets: *V* (Σ) of *visible* sorts, and *H*(Σ) of *hidden* sorts;
  + a many sorted (*V* ∪ *H*)-signature Σ;
  + an ΣT*V* -algebra *D*(Σ) called *data algebra*.

We simply write *V* , *H*, and *D* whenever Σ is understood from the context. Given a hidden-signature Σ, a *hidden* Σ*-model* is a Σ-algebra *M* such that *M* TΣ†*V* = *D*. This means that the interpretation of each sort *s* ∈ *V* ∪ *H* is a distinct set *Ms*, and the interpretation of a symbol *f* ∈ Σ*s*1 ···*sn,s* is a function [[*f* ]]*M* : *Ms*1 × ··· × *Msn* → *Ms*. We denote by *M*TΣ†*V* the algebra *M* restricted only to the visible sorts and visible operations. A *hidden* Σ*-homomorphism*

*h* : *M* → *M*' is a Σ-homomorphism such that *h*TΣ†

*V*

= id*D*. Given a hidden-

signature Σ and a subsignatu re Γ ⊆ Σ such that ΓT*V* = ΣT*V* , a Γ*-context for*

*sort s* is a term in TΓ({ : *s*} *Z*) having exactly one occurrence of a special

variable  of sort *s*. *Z* is an infinite set of distinct variables. CΓ[ : *s*] denotes the set of all Γ-contexts for the sort *s*. If *c* ∈ CΓ[ : *s*], then the sort of *c*, viewed as a term, is called the *result sort* of the context *c*. A Γ-context with visible result sort is called a Γ*-experiment*. If *c* ∈ CΓ[ : *s*] with the result sort

*s*' and *t* ∈T (*X*) , then *c*[*t*] denotes the term in T (*var*(*c*) ∪ *X*) obtained from

Σ *s* Σ

*c* by substituting *t* for  . Furthermore, for each hidden Σ-model *M*, *c* defines

a map **[***c*]]*M* : *Ms* → [*Mvar*(*c*) → *Ms*' ] defined by **[***c*]]*M* (*a*)(*ϑ*) = *aϑ*(*c*), where *aϑ*(*c*) is the variable assignment { '→ *a*}∪ {*z* '→ *ϑ*(*z*) | *z* ∈ *var*(*c*)}. We call [[*c*]]*M* the *interpretation* of the context *c* in *M*.

Given a hidden-signature Σ, Γ ⊆ Σ such that ΓT*V* = ΣT*V* , and a hidden Σ-model *M*, the Γ*-behavioral equivalence* on *M*, denoted by ≡Γ , is defined as

Σ

follows:

for any sort *s* ∈ *V* ∪ *H* and any *a, a*' ∈ *Ms*, *a* ≡Γ *a*' iff **[***c*]]*M* (*a*)(*ϑ*)= **[***c*]]*M* (*a*')(*ϑ*)

Σ

for all Γ-experiments *c* and

all (*V* ∪ *H*)-sorted maps *ϑ* : *var*(*c*) → *M*.

Given an equivalence ∼ on *M*, an operation *f* ∈ Σ*s*1*...sn,s* is *congruent wrt*

~ iff **[***f* ]]*M* (*a ,...,a* ) ∼ [[*f* ]] (*a*' *,..., a*' ), whenever *a* ∼ *a*' for *i* = 1*,..., n*.

1 *n M* 1 *n i* *i*

An operation *f* ∈ Σ is Γ*-behaviorally congruent wrt M* iff it is congruent wrt

≡Γ . A *hidden* Γ*-congruence* on *M* is a (*V* ∪ *H*)-equivalence on *M* that is an identity on visible sorts, and each operation in Γ is congruent wrt it.

Σ

Theorem 2.1 *[*[*8*](#_bookmark9)*,*[*14*](#_bookmark14)*] Given a hidden-signature* Σ*,a subsignature* Γ ⊆ Σ *such that* ΓT*V* = ΣT*V , and a hidden* Σ*-model M, then* Γ*-behavioral equivalence is the largest hidden* Γ*-congruence on M.*

A hidden Σ-model *M* Γ*-behaviorally satisﬁes* a Σ-equation *e* of the form (∀*X*)*t* = *t*' if *C*, where *C* is a set of pairs of Σ(*X*)-terms, if and only if for all *ϑ* : *X* → *M*, *ϑ*(*t*) ≡Γ *ϑ*(*t*') whenever *ϑ*(*u*) ≡Γ *ϑ*(*v*) for all (*u, v*) ∈ *C*. We

Σ Σ

write *M* |≡Γ *e*. If *E* is a set of Σ-equations, we write *M* |≡Γ *E* iff *M* |≡Γ *e* for

Σ Σ Σ

all *e* in *E*.

A *behavioral speciﬁcation* is a triplet B = (Σ*,* Γ*, E*) consisting of a hidden signature Σ, a subsignature Γ ⊆ Σ such that ΓT*V* = ΣT*V* and a set *E* of Σ- equations. We often denote the constituents of B by Σ(B)*,* Γ(B) and *E*(B), respectively. The operations in Γ \ (ΣT*V* ) are called *behavioral*. A hidden Σ- model *M behaviorally satisﬁes* the specification B iff *M* Γ-behaviorally satisfies *E*, that is *M* |≡Γ *E*. We write *M* |≡ B and we say that *M* is a B*-model*. For any equation *e*, we write B |≡ *e* iff *M* |≡ B implies *M* |≡ *e*. An operation *f* ∈ Σ is *behaviorally congruent* wrt B iff *f* is Γ-behaviorally congruent wrt each B-model *M*.

Σ

Behavioral specifications can model concurrent objects. B specifies a *sim- ple object* iff:

1. *H*(B) has a unique element *h* called *state sort*;
2. each operation *f* ∈ Σ \ ΣT*V* is either:
   1. a hidden (generalized) constant modeling an initial state, or
   2. a *method g* : *hv*1 ··· *vn* → *h* with *vi* ∈ *V* for *i* = 1*,..., n*, or
   3. an *attribute q* : *hv*1 ··· *vn* → *v* with *v, v*1*,* ··· *, vn* ∈ *V* .

In other words, the framework for simple objects is the monadic fixed-data hidden algebra [[14](#_bookmark14)]. A *concurrent connection* B1  ···  B*n* is defined as in [[7](#_bookmark10)] where the (composite) state sort is implemented as tupling. If *hi* is the state sort of B*i*, then a composite state is a tuple ⟨*st*1*,... , stn*⟩ : Tuple where the state *sti* is of sort *hi*. Projection operations *i*∗, *i* = 1*,... , n*, are defined by

projection equations *i*∗(⟨*st ,... , st* ⟩ = *st* together with “tupling equation”

1 *n* *i*

⟨1∗*st,... , n*∗*st*⟩ = *st*, where *st* is of sort Tuple. We assume that all specifica- tions B1*,... ,* B*n* share the same data algebra. For each component B*i* and *f* in B*i*, we consider an operation *f.*B*i* defined by:

*f.*B*i*(⟨*st*1*,... , stn*⟩*,* −→*x* )= *f* (*sti,* →−*x* ) if *f* is an attribute, and

*f.*B*i*(⟨*st*1*,... , stn*⟩*,* −→*x* )= ⟨*st*1*,... ,f* (*sti,* →−*x* )*,... , stn*⟩ if *f* is a method, where by −→*x* we denote a sequence of the form *x*1*,... , xn*.

Proposition 2.2 *[*[*8*](#_bookmark9)*] 1. If g is a method of* B*i, g*' *a method of* B*j, and i* /= *j,*

*then*

*g.*B (*g*'*.*B (*st,* −→*y* )*,* →−*x* )= *g*'*.*B (*g.*B (*st,* →−*x* )*,* −→*y* )

*i j j* *i*

*2. If q is an attribute of* B*i, g a method of* B*j, and i* /= *j, then*

*q.*B*i*(*g.*B*j*(*st,* −→*y* )*,* −→*x* )= *q.*B*i*(*st,* −→*x* )*.*

The first part of Proposition [2.2](#_bookmark0) allows us to consider the method *g.*B*i * *g*'*.*B*j*

such that *g.*B *g*'*.*B (*st,* −→*x,* →−*y* ) means the concurrent execution of *g.*B (*st,* −→*x* )

*i j* *i*

and *g*'*.*B*j*(*st,* −→*y* ). If *g.*B*i* and *g*'*.*B*j* are in Γ, then *g.*B*i * *g*'*.*B*j* is in Γ(B  *... * B*n*)

1

as well. Note that the new added functions *f.*B*i* could be non-behavioral in B

even if *f* is behavioral in B*i*.

By *object speciﬁcation* we mean either a simple object specification, or a conservative extension of a concurrent connection of object specifications. We extend an object specification by adding the following elements of interaction:

1. *Elements of synchronization* given by pairs (*a, a*) denoting the *necessity* and *availability* of the shared name *a*. Both *a* and *a* denote behavioral methods in different object components; the invocation of these methods expresses the necessity and the availability of *a* (it does not matter which one). An element *a* is called *closed synchronization* for B iff both *a* and *a* are present. If only one (either *a* or *a*) is present, then we have an *open synchronization*. Let *Synch*(B) denote the set of the synchronization elements of B.
2. *Elements of communication* given by pairs (*a, a*) denoting the *receiving* and *sending* of a value along the communication channel *a*. Now *a* de- notes a behavioral method and *a* denotes a behavioral attribute; the value supplied by the attribute is passed to the second component as an argu- ment of the calling method. A communication channel *a* is called *closed communication* for B iff both *a* and *a* are present. If only one element of a communication pair (either *a* or *a*) is present, then we have an *open com- munication*. Let *Comm*(B) denote the set of the communication elements of B.

We use the BOBJ language ([http://www.cs.ucsd.edu/groups/tatami/bobj/) to](http://www.cs.ucsd.edu/groups/tatami/bobj/)to) ex- press the behavioral specifications. We enrich the BOBJ syntax by adding the synchronization capabilities by synch attributes of the corresponding meth- ods, and the communication capabilities by comm: ~a and comm: index ->

a. The index in comm: index -> a is used to identify the receiving com- ponent linked to the corresponding comm: ~a. Our extension of the BOBJ language uses ~a to denote a. We consider methods receiving along at most a single communication channel. However the attributes may send values along more than one communication channel.



S



M

M

M

V

Fig. 1. Triple Modular Redundancy

Example 2.3 Triple Modular Redundancy.

The following example exhibits how the synchronization and communication elements are used. Triple Modular Redundancy (TMR) is a popular technique in fault tolerance. Three copies of a module M are put together using a splitter S and a voter V (see Figure [1](#_bookmark1)). The splitter sends the input value to each copy of the system module M. There is no fixed order in which the splitter sends the input value to the three copies of M. A faulty M either behaves correctly or may output an arbitrary value. The voter accepts the results from each of these copies of M, and outputs the majority value. The behavioral specification of the system is:

dth DATA is sort Data .

sort ModuleId . ops 0 1 : -> Data .

ops 1 2 3 : -> ModuleId .

op vop : Data -> Data . \*\*\* equations defining vop are missing end

bth MOD1 is sort Mod1 . inc DATA .

op put : Mod1 Data -> Mod1 . [comm: 1 -> mi1] op hop : Mod1 -> Mod1 . [synch: w1]

op get : Mod1 -> Data . [comm: ~mo1] var M : Mod1 . var D : Data .

eq get(put(M, D)) = D . end

\*\*\* MOD2 and MOD3 are defined in a similar way as MOD1 bth SPLITTER is

sort Splitter .

inc DATA .

op rec : Splitter Data -> Splitter . [comm: 1 -> in]

op split : Splitter -> Data . [comm: ~mi1, ~mi2, ~mi3] op rack : Splitter -> Splitter . [synch: ack]

var S : Splitter . var D : Data . eq split(rec(S, D)) = D .

end

bth VOTER is sort Voter . inc DATA .

op rec1 : Voter Data -> Voter . [comm: 1 -> mo1] op rec2 : Voter Data -> Voter . [comm: 1 -> mo2] op rec3 : Voter Data -> Voter . [comm: 1 -> mo3] op val : Voter -> Data . [comm: out]

var V : Voter . vars D1 D2 D3 : Data . eq val(rec3(rec2(rec1(V, D1), D2), D3)) =

if (D1 == D2) then D1 else D3 fi .

op sack : Voter -> Voter . [synch: ~ack] end

bth TMR is

inc (SPLITTER || MOD1 || MOD2 || MOD3 || VOTER) \* (sort Tuple to Tmr) . end

MOD1 specifies a simple TMR module that receives an input data from somewhere and executes an operation (method) hop over these values. Nor- mally we expect the result of the operation hop( ) to be vop(get(hop( ))), but unfortunately the system may have faults and therefore the result is un- predictable. This nondeterministic property is implicitly expressed by the fact that we have no equation regarding the effect of hop. The comm at- tributes are introduced to describe the communication elements of the mod- ule. For instance, comm: 1 -> mi1 specifies that the 1st visible argument of the method put is the value passed by someone else using the communica- tion channel ~mi1. This value is bound to the 1st argument of the method. comm: ~mo1 specifies that the module sends along the communication channel mo1 the value returned by the attribute get for the current state. We have *synch*(hop*.*MOD1) = w1, *comm*(put*.*MOD1) = 1 → mi1, *comm*(get*.*MOD1) =

~mo1, *Synch*(MOD1) = {w1}, *Comm*(MOD1) = {mi1*,* ~mo1}. The splitter re-

ceives a value along in, passes this value along ~mi1, ~mi2, ~mi3, and waits for an acknowledgment along ack. The voter receives data along mo1, mo2, mo3, and sends the majority value along ~out; then it sends an acknowledg- ment along ~ack. The effective actions are made by the operations behind these synchronization and communication elements.

# CCS

The Calculus of Communicating Systems (CCS) was originally developed in the ’80s by Milner [[12](#_bookmark13)]. CCS provides a minimal formal framework to describe and study synchronized and communicating concurrent processes and various behavioral equivalences. Interaction among processes is established by a non-

*P* −*α P* ′

→

*P* −*α P* ′

→

*α*

*α.P* − *P*

→

*α*

*P* + *Q* − *P* ′

→

*α*

*P* |*Q* − *P* ′|*Q*

→

{ *b / a* }*PA* −→ *P A*(−→*a* ) d=ef *P*

→− →−

*α*

′

*P* −→ *P*

*α*

′

*A*

⟨ *b* ⟩ −

−→

*A*

→ *P*

*α*

′

new *L P* −*α* new *L P* ′

*α* /∈ *L* ∪ *L*

→

*P* −*α P* ′

→

*Q* −*α Q*′

→

*P* =⇒

*τ* ∗ *P* ′

*P* ′ −*α Q*′

→

*Q*′

=⇒

*τ* ∗ *Q*

*P* |*Q* −*τ*

→ *P* ′|*Q*′

*P* =⇒ *Q*

*α*

Fig. 2. CCS operational semantics

deterministic matching between complementary ends of some synchronization and communication channels. When there are many pairs which can satisfy the matching condition, only a single pair (*a, a*) is selected.

We assume a set A of *names*; the elements of the set A = {*a* | *a* ∈ A} are called *co-names*, and the elements of the set L = A∪ A are *labels* naming ordinary actions. The standard definition of CCS includes only one special action called *silent action* and denoted by *τ* , intended to represent an internal action of the system.

The *processes* are defined over the set *A* of names by the following syntac- tical rules:

*P* ::= 0 | *α.P* | *P* + *Q* | *P* |*Q* | new *L P* | *A*⟨*a*1*,... , an*⟩

where *P* and *Q* range over processes, *α* over actions, *ai* over names, *L* over sets of names, and *A* over process identifiers.

A structural congruence relation is defined over the set of processes. The relation ≡ over the set of processes is called *structural congruence*, and is defined as the smallest congruence which satisfies:

*P* ≡ *Q* if *Q* can be obtained from *P* by *α*-conversion,

*P* +0 ≡ *P* , *P* + *Q* ≡ *Q* + *P* , (*P* + *Q*)+ *R* ≡ *P* + (*Q* + *R*),

*P* | 0 ≡ *P* , *P* | *Q* ≡ *Q* | *P* , (*P* | *Q*) | *R* ≡ *P* | (*Q* | *R*).

The structural operational semantics is shown in Figure [2](#_bookmark2), where we have already assumed that the summation and parallel composition are associative

−→ −→

−→ −→

and commutative. If

*a* = (*a*1*,... , an*) and

*b* = (*b*1*,... , bn*), then { *b / a* }*P*

denotes the simultaneous substitution *P* [*b*1*/a*1*,... , bn/an*]. We also assume

that every process identifier *A* has a defining equation of the form *A*(−→*a* ) d=ef *P*

*A*

where *PA* is a summation of processes, and −→*a* = (*a*1*,... , an*) includes all the free names in *PA*.

*Strong bisimulation*, written ∼, is defined over the processes as the largest

symmetrical relation such that: if *P* ∼ *Q* and *P* −→*α P* ', then there exists *Q*'

such that *Q* −→*α Q*' and *P* ' ∼ *Q*'. *Weak bisimulation*, written ≈, is defined

over the processes as the largest symmetrical relation such that: if *P* ≈ *Q* and

*P* −→*α P* ', then there exists *Q*' such that *Q* =*α*⇒ *Q*' and *P* ' ≈ *Q*'.

In our formalism, we provide a computational structure to the CCS ac- tions, and it is enough to consider pure CCS to model the synchronization and communication between concurrent objects. According to the computa- tional structure behind each action, it is possible to decide the type of an interaction. The synchronization elements are provided by pairs (*a, a*) with each component associated with a method; in this way we have a method- method interaction. The communication elements are also provided by pairs (*a, a*); however, now *a* is associated with an attribute, and *a* is associated with a method.

Hennessy-Milner Modal Logic (HML) is a simple modal logic of actions used for describing local capabilities of CCS processes. HML formulas are as follows:

*ϕ* ::= tt | ff | *ϕ*1 ∧ *ϕ*2 | *ϕ*1 ∨ *ϕ*2 | [*α*]*ϕ* | ⟨*α*⟩*ϕ* | [[*α*]]*ϕ* | ⟨⟨*α*⟩⟩*ϕ*

If *P* is a CCS process and *ϕ* a HML formula, the satisfaction relation *P* |= *ϕ*

is inductively defined as:

*P* |= tt

*P* |= *ϕ*1 ∧ *ϕ*2 iff *P* |= *ϕ*1 and *P* |= *ϕ*2 *P* |= *ϕ*1 ∨ *ϕ*2 iff *P* |= *ϕ*1 or *P* |= *ϕ*2

*P* |= [*α*]*ϕ* iff (∀*P* '

∈ {*P* ''

*α*

| *P* −→ *P*

''}

) *P* ' |= *ϕ*

*P* |= ⟨*α*⟩*ϕ* iff (∃*P* '

∈ {*P* ''

*α*

| *P* −→ *P*

''}

) *P* ' |= *ϕ*

*P* |= [[*α*]]*ϕ* iff (∀*P* ' ∈ {*P* '' | *P α*

=⇒ *P*

*P* |= ⟨⟨*α*⟩⟩*ϕ* iff (∃*P* ' ∈ {*P* '' | *P α*

=⇒ *P*

''} ''

) *P* ' |= *ϕ*

) *P* ' |= *ϕ*

# HiddenCCS Specifications

}

The integration of CCS and object specification in hidden algebra is given by the elements of synchronization and communication. A CCS process over the elements of synchronization and communication works as a coordinating module that manages the interaction between objects. A *hiddenCCS spec- iﬁcation* is a triple (B*,* P*,* IC) consisting of objects specifications B given in hidden algebra, a CCS description P of the coordinating module, and a set IC of integration consistency requirements. The semantics of hiddenCCS spec-

ifications is given by a labeled transition system defined over configurations (hidden state, CCS process) as follows:

−→

1. If

*α*

*P* −→ *P*

' and *α* is open, then (*st, P* ) *α*

(*st*'*,P* '), where *st*' is obtained

from *st* by applying the method associated to *α*.

1. If

*α* ',

*α* ', and *α* is closed, then (*st, P* | *Q*) *τ*

(*st*'*,P* ' | *Q*'),

where *st*' is obtained from *st* by synchronously applying the methods associated to *α* and *α* whenever the integration consistency requirements are satisfied.

*P*

−→ *P*

*Q* −→ *Q*

−→

1. If *P* −→*a P* ', *Q* −→*a*

*Q*' where *k*→*a* = *comm*(*g*) and *a* ∈ *comm*(*q*), then

*τ*

(*st, P* | *Q*) −→

(*st*'*,P* ' | *Q*') such that *st*' is obtained from *st* applying the

method *g* having the *k*th argument provided the attribute *q*, whenever the integration consistency requirements are satisfied. Moreover, the sort of the *k*th argument of *g* should be equal to the sort of *q*.

This definition is sound if each (co-)name is uniquely associated to a method or attribute. Whenever the same name *a* is related to more than one method, e.g., to the methods *g*1*,... , gn*, then we consider *n* distinct copies *a*1*,..., an* of the name *a*, each of them for the corresponding method, and we define a relation eq given by *ai* eq *a* for *i* = 1*,... , n*. The operational semantics of CCS is modified as follows. The “synchronization” rule is replaced with:

*αi* '

*αj* '

*P* −→ *P Q* −→ *Q*

*αi* eq *α* and *αj* eq *α*

*τ* (*αi,αj* ) ' '

*P* |*Q* −−−−→ *P* |*Q*

For the silent action *τ* we use a more exact notation *τ* (*αi, αj*) indicating the names involved in such an internal action. This notation is necessary to inte- grate CCS semantics with the behavioral semantics of hidden algebra. Since *τ* is used in the definition of the CCS bisimulation, the following rules restore it from *τ* (*αi, αj*), where *α*∗ = if (*α* = *τ* (*αi, αj*)) then *τ* else *α*:

*τ* (*αi,αj* )

*τ* ∗ '

' *α* '

' *τ* ∗

*P* −−−−→ *Q*

*τ*

*P* =⇒ *Q*

*P* =⇒ *P P* −→ *Q Q* =⇒ *Q*

*α*∗

*P* =⇒ *Q*

A *CCS*(B)*-process* is a CCS process built over the set *Synch*(B) ∪ *Comm*(B).

An *integration consistency requirement* expresses the availability of an inter- action resource and consists of a finite set of equations *q*( *, d*1*,... , dn*) = *d*, where *q* is an attribute in Γ, and *d, d*1*,... , dn* ∈ *D*(B). Let *ic*(*a, a*) denote the integration consistency requirement corresponding to the interaction pair (*a, a*). A state *st* of a model *M satisﬁes ic*(*a, a*) whenever **[***q*]]*M* (*st, d*1*,..., dn*)= *d* for each *q*( *, d*1*,... , dn*) = *d* in *ic*(*a, a*); we write *st* |= *ic*(*a, a*). Our TMR example does not use the integration consistency requirements. An example of integration consistency requirement is offered by a critical resource where it is expressed by an equation of the form isAvailable( ) = true meaning

that the critical resource may interact only if it is available in the current state. Such an example is presented in [[2](#_bookmark5)].



−→

*g* : *h v* → *h , synch*(*g*)= *α, st* = [[*g.*B ]] (*st, ,*

−→

′

*i*

*i*

*i M*

*d* ) *P* −*α P* ′

→

(*st, P* ) −*α* (*st*′*,P* ′)

→

−→

*g* : *h v* → *h , comm* (*g*)= *k*→*a, st* = [[*g.*B ]] (*st, ,*

*i*

−→

′

*i*

*i M*

*d* ) *P* −*a P* ′

→

(*st, P* ) −*a* (*st*′*,P* ′)

→

*q* : *h* −→*v* → *h , a* ∈ *comm*(*q*)*, P* −*a P* ′

*i* *i*

→

(*st, P* ) −*a* (*st, P* ′)

→

−→

*g* : *h v* → *h* ∈ Γ noninteracting*, st* = [[*g.*B ]] (*st,*

−→

′

*i*

*i*

*i M*

*d* )

*idle*

(*st, P* ) (*st*′*,P* )

−−→

*g* : *h v* → *h , synch*(*g*)= *α , g* : *h v* → *hj, synch*(*g* )= *αj,*

−→

′

−→′

′

*i*

*i*

*i*

*j*

*st* |= *ic*(*αi, αj*)*, st* = [[*g.*B*i g .*B*j*]]*M* (*st, d, d* )*, P* −−−−−→ *P*

→ (*st*′*,P* ′)

′

′

−→ −→′

*τ* (*αi,αj* ) ′

(*st, P* ) −*τ*

*g* : *hi*−→*v* → *hi, comm*(*g*)= *k*→*ai, q* : *hj*−→*v* → *v , a* ∈ *comm* (*q*)

′

′

*j*

*st* |= *ic*(*ai, aj*)*, st* = [[*g.*B*i*]]*M* (*st, d* ) where *dk* = [[*q.*B*j*]]*M* (*st, d* )*,*

→ (*st*′*,P* ′)

′

−→

−→′

*P* −−−−−→ *P*

*τ* (*ai,aj* ) ′

*τ*

(*st, P* ) −

(*st ,P* ) (−*τ*

1

→ ∪ −−→

*idle* )∗ (*st*′ *, P* ′) (*st*′ *, P* ′) −*α* (*st*′ *, Q*′) (*st*′ *, Q*′) (−*τ*

1

1

→

2

2

→ ∪ −−→

*idle* )∗ (*st , Q*)

2

(*st ,P* ) *α*

1

=⇒ (*st , Q*)

2

Fig. 3. HiddenCCS operational semantics

Given an object specification B and a hidden B-model *M*, we denote by *LT S*Γ*,CCS*(*M*) the labeled transition system defined by the rules in Figure [3](#_bookmark3), where *P* , *P* ' and *Q* are CCS(B)-processes, and −→ and −→' are sequences of data

*d*

*d*

values from *D*(B). The transitions corresponding to noninteracting behavioral

methods are labeled by *idle*. If *st* is a state in *M* and *P* is a CCS process, then *LT S*Γ*,CCS*(*M, st, P* ) denotes the subsystem induced by the subset of the configurations which are reachable from (*st, P* ).

Definition 4.1 Let Σ be an object signature, Γ a subsignature of Σ, and let

*h*

*M* and *M*' be two Σ-models. The relation Σ*,*Γ

*M,M*

' ⊆ *Mh* × *M*'

is defined by:

Σ*,*Γ ' '

*st* *M,M* ' *st* iff **[***q*]]*M* (*st, d*1 *..., dn*) = **[***q*]]*M*' (*st , d*1 *... , dn*) for any attribute

*q* ∈ Γ, and data values *d*1*,... , dn* ∈ *D*(B).

Definition 4.2 Given an object specification B = (Σ*,* Γ*, E*), and two B- models *M* and *M*', then the *behavioral CCS-based strong* Γ*-bisimulation* be-

'

tween *M* and *M*

(*st*' *,P* ') implies

1

is the largest relation ∼*M,M*' such that (*st*1*,P* ) ∼*M,M*'

1. *st*1

Σ*,*Γ

*M,M*

' *st*' ,

1. if (*st ,P* ) −→*α* (*st , Q*) then there is (*st*' *, Q*') such that (*st*' *,P* ') −→*α* (*st*' *, Q*')

1

1 2 2 1 2

' '

and (*st*2*, Q*) ∼*M,M*' (*st*2*,Q* ), and

1. if (*st*' *,P* ') *α* (*st*' *, Q*') then there is (*st , Q*) such that (*st ,P* ) *α*

(*st , Q*)

1 −→ 2 2

' '

1 −→ 2

and (*st*2*, Q*) ∼*M,M*' (*st*2*,Q* ).

We say that a state *st* is *consistent* with a process *P* iff for each configura- tion (*st*'*,P* ') reachable from (*st, P* ), *st*' satisfies the integration consistencies required by *P* '. A ground term *t* of state sort is *consistent* with a process *P* iff **[***t*]]*M* is consistent with a *P* for each B-model *M*.

Proposition 4.3 *Given an object speciﬁcation* B = (Σ*,* Γ*, E*)*, two CCS*(B)*- processes P and P* '*, and two* B*-models M and M* '*, then P* ∼ *P* ' *whenever there are st in M and st*' *in M* ' *such that st is consistent with P, st*' *is consistent*

' ' '

*with P , and* (*st, P* ) ∼*M,M*' (*st ,P* )*.*

' '

Proof. Let us consider (*st, P* ) ∼*M,M*' (*st ,P* ) such that *st* is consistent with

1. and *st*' is consistent with *P* '. We have to show that *P* ∼ *P* '. Let *R* be

the relation defined by *Q R Q*' iff there are *st* and *st*'

1

1

such that (*st*1*, Q*) ∈

' ' ' ' '

*LT S*Γ*,CCS*(*M, st, P* ), (*st*1*,Q* ) ∈ *LT S*Γ*,CCS*(*M , st ,P* ), and (*st*1*, Q*) ∼*M,M*'

(*st*' *, Q*'). We show that if *Q R Q*' and *α* , then there is *Q*' such that

1 1 1

*Q*1 −→ *Q*2 2

1. −→*α Q*' and *Q RQ*' . Let *Q ,Q , Q*'

be such that *Q RQ*' and *Q*

−→*α*

*Q* . By

2 2 2 2

1 2 1

1 1 1 2

definition of *R* there are *st* and *st*'

1 1

' ' ' ' '

such that (*st*1*, Q*1) ∈ *LT S*Γ*,CCS*

' '

(*M, st, P* ),

(*st*1*, Q*1) ∈ *LT S*Γ*,CCS*(*M , st ,P* ), and (*st*1*, Q*1) ∼*M,M*' (*st*1*, Q*1). We distin-

guish the following cases:

*a*

* 1. *α* = *a*. Let *g* be the method in B*i* associated to *a*. We have (*st*1*, Q*1) −→

−→ −→

(*st ,Q* ), where *st* = [[*g.*B ]] ( ) for certain . There is (*st*' *, Q*' )

2 2 2

' ' *α*

*i M st*1*, d*

' '

*d* 2 2

' '

such that (*st*1*, Q*1) −→ (*st*2*, Q*2) and (*st*2*, Q*2) ∼*M,M*' (*st*2*, Q*2) by the def-

inition of ∼*M,M*' . Since *a* is uniquely associated to *g*, it follows that

' ' −→

' *a* ' '

*st*2 = [[*g.*B*i*]]*M*' (*st*1*, d* ) and *Q*1 −→ *Q*2. Hence *Q*2 *R Q*2.

The case *α* = *a* is similar.

* 1. *α* = *τ* . We suppose that *τ* is restored from *τ* (*αi, αj*). Since *st* is consistent with *P* and (*st*1*, Q*1) is reachable from (*st, P* ), it follows that *st*1 |= *ic*(*αi, αj*) which implies the existence in *LT S*Γ*,CCS*(*M*) of a transition

*a* ' '

(*st*1*, Q*1) −→ (*st*2*, Q*2). Since (*st*1*, Q*) ∼*M,M*' (*st*1*,Q* ), it follows that there

' ' ' ' *a* ' ' ' '

is (*st*2*, Q*2) such that (*st*1*, Q*1) −→ (*st*2*, Q*2) and (*st*2*, Q*2) ∼*M,M*' (*st*2*, Q*2).

By the definition of our transition system, there exists (*α*'*, α*' ) such that

*i j*

*τ* (*α*' *,α*' )

*Q*' −−−−→ *Q*' . It follows that ' *τ* ' by the restoring rule, and

*i j*

1

*Q R Q*'

2

2

2

by definition of *R*.

*Q*1 −→ *Q*2

Therefore we obtained that there is *Q*' such that *α* and *Q R Q*'

'

in all

2 *Q*2 −→ *Q*2 2 2

cases. It follows that *R* ⊆ ∼.

Proposition 4.4 *Given an object speciﬁcation* B = (Σ*,* Γ*, E*)*, and a* B*-model*

*M, then* (*st, P* ) ∼*M,M* (*st*'*,P* ') *whenever st* ≡Γ *st*' *and P* ∼ *P* '*.*

Σ

Proof. We define the relation *R* by (*st, P* ) *R* (*st*'*,P* ') iff *st* ≡Γ *st*' and *P* ∼

Σ

*M,M*

*P* '. If (*st, P* ) *R* (*st*'*,P* ') then *st* Σ*,*Γ

*M,M*

*st*' because Σ*,*Γ

is included in the

behavioral equivalence. We suppose that (*st ,P* ) *R* (*st*' *,P* ') and (*st ,P* ) *α*

1 1 1 1

(*st*2*, P*2). We have the following cases:

1 1 −→

1. *α* = *a*. Let *g* be the method in B*i* associated to *a*. Then *st*2 =

−→

[[*g.*B*i*]]*M* (*st*1*, d* ) for certain

−→

*d* , and *P*1

*a*

−→ *P*2 by the definition of the

transition system. Since *P*

~ *P* ', there is *P* ' such that *P* ' −→*a P* ' and

1 1 −→ 2 1 2

*P* ∼ *P* '. We consider *st*'

= [[*g.*B ]] (*st*' *, d* ). We have *st* ≡Γ *st*'

be-

2 2 2

*i M* 1

*a* 2 Σ 2

cause *st* ≡Γ *st*'

and *g* is behavioral. It follows (*st*' *,P* ') −→ (*st*' *,P* ') and

1 Σ 1

1 1 2 2

(*st ,P* ) *R* (*st*' *,P* '). The case *α* = *a* is similar.

2 2 2 2

1. *α* = *τ* . By the definition of the transition system, there exists (*αi, αj*)

such that

*τ* (*αi,αj* )

' ' *τ* (*αi,αj* ) '

*P*1 −−−−→ *P*2. Then there is *P*2 such that *P*1 −−−−→ *P*2

because *P*

~ *P* '. Since *st* ≡Γ *st*' , it follows that *st*' |= *ic*(*α ,α* ). A

1 1 1 Σ 1 1 *i j*

reasoning similar to that of the previous case implies that there are *st*'

' ' ' *τ* ' '

' ' 2

and *P*2 such that (*st*1*, P*1) −→ (*st*2*, P*2) and (*st*2*, P*2) *R* (*st*2*, P*2).

1. *α* = *idle*. We have *P*1 = *P*2. Then there is a noninteracting method *g*

−→ →−

in B*i*, for certain *i*, and *d* such that *st*2 = [[*g.*B*i*]]*M* (*st*1*, d* ). We take

*P* ' = *P* ' and *st*' = [[*g.*B ]] ( ' −→). We have (*st ,P* ) *R* (*st*' *,P* ') because

2 1 2

*i M st*1*, d*

2 2 2 2

*g* is behavioral.

We obtained in all the cases that there are *st*'

and *P* ' such that (*st*' *,P* ') −→*α*

' ' ' '

2 2 1 1

(*st*2*, P*2) and (*st*2*, P*2) *R* (*st*2*, P*2). Therefore *R* ⊆ ∼.

Remark 4.5 The converse of Proposition [4.4](#_bookmark4) is not generally true [[9](#_bookmark11)]. This is due to the fact that we may have ∼*M,M*' /= ≡Γ .

Σ

# Describing the LTS in Rewriting Logic

Rewriting logic [[4](#_bookmark7)] is a logic able to deal with the concurrent changes of states and with concurrent computations. It has good properties, and provides a general semantic framework for executable implementations of a wide range

of languages and models of concurrency. In particular, it supports the imple- mentations of CCS and HML [[16](#_bookmark15)].

Maude [[4](#_bookmark7)] is a system extending OBJ3 with support for membership equa- tional logic and rewriting logic. A distinguished feature of Maude is the use of the reflection property of the rewriting logic for creating executable envi- ronments for different logics, theorem provers, and models of computations. However, the current version of Maude does not support yet the hidden logic used by BOBJ for behavioral specification and verification.

We denote by R(P)= (Σ(P)*, E*(P)*, R*(P)) the rewriting specification as- sociated with the CCS specification P as in [[16](#_bookmark15)], and by |=*HML* the deduc- tion relation for HML. The sort of the CCS processes in *R*(P) is denoted by

*α*

Process. succ(*P, α*) is the function which returns the set {*Q* | *P* −→ *Q*}. Let

*SP* = (B*,* P*,* IC) be a hiddenCCS specification where B = (Σ*,* Γ*, E*) and the state sort of B is *h*. We associate with *SP* a rewriting specification R(*SP* )= (Σ'*, E*'*, R*), where Σ' is Σ ∪ Σ(P) ∪ Σ(*HML*) together with a new sort St and a new operation ( *,* ): *h* Process → St, and *E*' = *E* ∪ *E*(P) ∪ *E*(*HML*). *R* includes the following rules:

1. if *g* : *hiv*1 *... vn* → *hi* is a method in B*i* such that *synch*(*g*) = *α* or

*comm*(*g*)= *k*→*α* and *α* is open, then we add rewriting rules of the form:

*α* : (*st, P* ) → (*g.*B*i*(*st, d*1*,..., dn*)*, Q*) if *P* |=*HML* ⟨*α*⟩tt ∧ *Q* ∈ *succ*(*P, α*)

for appropriate *d*1*,... , dn* ∈ *D*(B);

1. if *q* : *hiv*1 *... vn* → *v* is an attribute in B*i* such that *a* ∈ *comm*(*q*) and *a* is open, then we add rewriting rules of the form:

*a* : (*st, P* ) → (*st, Q*) if *P* |=*HML* ⟨*a*⟩tt ∧ *Q* ∈ *succ*(*P, a*)

1. if *g* : *hiv*1 *... vn* → *hi* is a noninteracting method in Γ, then we add a rewriting rule of the form:

*idle* : (*st, P* ) → (*g.*B*i*(*st, d*1*,... , dn*)*,P* ) for appropriate *d*1*,... , dn* ∈ *D*(B).

1. if *g* : *h v ... v* → *h* is a method in B with *synch*(*g*) = *α* , *g*' :

*i* 1 *n i i* *i*

*hjv*' *... v*' ' → *hj* is a method in B*j* with *synch*(*g*') = *αj*, and there is

1 *n*

*α* such that *αi* eq *α* and *αj* eq *α*, then we add rewriting rules of the

form:

*τ* : (*st, P* ) → (*g.*B *g*'*.*B (*st, d ,... ,d , d*' *,... , d*' ')*, Q*)

*i j* 1

*n* 1 *n*

if *P* |=*HML* ⟨*τ* (*αi, αj*)⟩tt ∧ *Q* = *succ*(*P, τ* (*αi, αj*)) ∧ *ic*(*αi, αj*)

for appropriate *d ,... ,d , d*' *,... , d*' ' ∈ *D*(B);

1 *n* 1 *n*

1. if *g* : *hiv*1 *... vn* → *hi* is a communicating method with *comm*(*g*)= *k*→*ai*, *q* in B*j*, *aj* ∈ *comm*(*q*), and there is *a* such that *ai* eq *a* and *aj* eq *a*, then we add rewriting rules of the form:

*τ* : (*st, P* ) → (*g.*B*i*(*st, d*1*,... , dn*)*, Q*)

if *P* |=*HML* ⟨*τ* (*ai, aj*)⟩ tt ∧ *Q* ∈ succ(*P, τ* (*ai, aj*)) ∧ *ic*(*ai, aj*)

where *dl* ∈ *D*(B)*v* if *l* /= *k*, and *dk* = *q.*B*j*(*st, d*' *,... , d*'

) for appropriate

' ' *Æ* 1 *m*

*d*1*,..., dm* ∈ *D*(B);

Remark 5.1 1. If *D*(B) is infinite, then R(*SP* ) could include an infinite number of rewriting rules. A particular case when the number of rules is finite is that when all the communicating methods in Γ have all the visible argu- ments bound to communication channels, the communicating attributes in Γ are unary – i.e., the only argument is the current state, the communication elements are closed, and Γ does not include noninteracting methods.

2. We note that R(*SP* ) forgets the behavioral operations. This has some dras- tic semantic consequences; e.g., not all R(*SP* )-models produce *SP* -models. Therefore we restrict the semantics of R(*SP* ) to those models where the states behaviorally satisfy the equations *E*. This restriction together with Proposition [4.4](#_bookmark4) make sound the following deduction rule:

*st*' ≡ *st α* : (*st ,P* ) −→ (*st , Q*) *st* ≡ *st*'

1 1 1 2 2 2

*α* : (*st*' *,P* ) −→ (*st*' *, Q*)

1 2

The use of this rule can reduce the state space within a model checking algo- rithm over the rewriting specifications according to the approach presented in [[10](#_bookmark12)].

We use the TMR example to exhibit how the Maude system can be used to build R(*SP* ). We first modify the Maude module implementing the oper- ational semantics of CCS by replacing the rule for synchronization and com- munication with the following two rules:

crl P | Q => {tau(L)}(P’ | Q’) if P => {L}P’ /\ Q => {~ M}Q’ /\ L eq M . crl P | Q => {tau(M)}(P’ | Q’) if P => {L}P’ /\ Q => {~ M}Q’ /\ L eq M .

where L eq M represents the implementation of the eq relation. Then we change the definition of *τ* , representing it by a function having as argument one

of the actions involved in synchronization. This is not a restriction, because

*τ* (*αi,αj* )

'

*P* | *Q* −−−−→ *P*

| *Q*'

*τ* (*αi*)

is the same as *P* | *Q* −−−→ *P*

'

| *Q*'

*τ* (*αj* )

and *P* | *Q* −−−→ *P* |

'

*Q*'. Moreover, we have *τ* (*α*)= *τ* (*α*).

The Maude description of the CCS expressions for TMR is as follows:

mod TMR-CCSPROC is inc CCS .

ops in out mi1 mi2 mi3 mo1 mo2 mo3 w1 w2 w3 ack : -> Label . ops S S1 S2 M1 M2 M3 V TMR : -> ProcessId .

eq context = ( S =def in . S1 ) &

( S1 =def ~ mi1 . ~ mi2 . ~ mi3 . S2 + ~ mi1 . ~ mi3 . ~ mi2 . S2 +

~ mi2 . ~ mi1 . ~ mi3 . S2 + ~ mi2 . ~ mi3 . ~ mi1 . S2 +

~ mi3 . ~ mi1 . ~ mi2 . S2 + ~ mi3 . ~ mi2 . ~ mi1 . S2 ) & ( S2 =def ack . S ) & ( M1 =def mi1 . w1 . ~ mo1 . M1 ) &

( M2 =def mi2 . w2 . ~ mo2 . M2 ) & ( M3 =def mi3 . w3 . ~ mo3 . M3 ) &

( V =def mo1 . mo2 . mo3 . out . ~ ack . V ) & ( TMR =def ( S | M1 | M2 | M3 | V )

\ mi1 \ mi2 \ mi3 \ mo1 \ mo2 \ mo3 \ ack ) .

endm

Note that the operator new *L P* is represented by the restriction *P* \ *L*. The Maude description of the rewriting specification associated with the TMR hiddenCCS specification is :

mod TMR-CCS is

pr TMR-TEST . pr MODAL-LOGIC .

sort CcsTmr .

op <\_‘,\_> : Tmr Term -> CcsTmr .

op 1\*\_ : CcsTmr -> Tmr . op 2\*\_ : CcsTmr -> Term .

var C : CcsTmr . vars A A’ : Tmr . vars P P’ Q Q’ : Term . eq < 1\* C, 2\* C > = C .

eq 1\* < A, P > = A . eq 2\* < A, P > = P .

crl [in] : < A, P > =>

< < rec(1\* A, 0), 2\* A, 3\* A, 4\* A, 5\* A >,succ(P,’in.Label) > if P |= < ’in.Label > tt .

\*\*\* missing one ’in’ rule

crl [out] : < A, P > => < A, succ(P,’out.Label) > if P |= < ’out.Label > tt .

crl [w1] : < A, P > =>

< < 1\* A, hop(2\* A), 3\* A, 4\* A, 5\* A >,succ(P,’idle1.Label) > if P |= < ’idle1.Label > tt .

\*\*\* missing two ’idle’ rules crl [tau] : < A, P > =>

< < 1\* A, put(2\* A, split(1\* A)), 3\* A, 4\* A, 5\* A >, succ(P,’tau[’mi1.Label]) >

if P |= < ’tau[’mi1.Label] > tt .

\*\*\* missing five ’tau’ rules crl [tau] : < A, P > =>

< < rack(1\* A), 2\* A, 3\* A, 4\* A, sack(5\* A) >, succ(P,’tau[’ack.Label]) >

if P |= < ’tau[’ack.Label] > tt .

endm

The Maude module MODAL-LOGIC describes HML and “|=” is the Maude im- plementation of the relation |=*HML*. Since HML is implemented at the met- alevel, the names used in the CCS terms are quoted. In this example the successor is unique. We have to include a rule for each successor when we have more successors.

Maude has some useful commands to analyze the dynamics of the rewrit- ing specifications. Here we use the search command to generate possible evolutions for the TMR system:

search [50] < init, ’TMR.ProcessId > =>+ ST:CcsTmr .

Maude provided 50 solutions possible:

...

Solution 50 (state 50)

states: 51 rewrites: 4079783942 in 8365430ms cpu (8438250ms real) (487695 rewrites/second)

ST:CcsTmr --> < < rec(rack(rec(initS, 1)), 0),put(hop(put(initM1, 1)), 0), put(hop(put(initM2, 1)), 0),hop(put(initM3, 1)),sack(rec(initV, get(hop(put(initM1, (1).Data))), get(hop(put(initM2, (1).Data))), get(hop(put(initM3, (1).Data))))) >, ’\_\\_[’\_\\_[’\_\\_[’\_\\_[’\_\\_[’\_\\_[’\_\\_[’\_|\_[’M3.ProcessId,

’V.ProcessId,’\_.\_[’w1.Label,’\_.\_[’~\_[’mo1.Label],’M1.ProcessId]],

’\_.\_[’w2.Label,’\_.\_[’~\_[’mo2.Label],’M2.ProcessId]],’\_.\_[’~\_[’mi3.Label],

’S2.ProcessId]],’mi1.Label],’mi2.Label],’mi3.Label],’mo1.Label], ’mo2.Label],’mo3.Label],’ack.Label] >

The execution performance of Maude is not encouraging. A reason for this weak performance is that CCS and LTL model checker are implemented at the metalevel. Built-in CCS module and LTL model checker could improve the Maude execution time.

A Linear Temporal Logic (LTL) model checker is implemented in Maude [[6](#_bookmark8)], and it can be used to verify temporal properties of the rewriting specifi- cations. The atomic temporal propositions for the state sort *h* are equations having one of the forms:

*q*(*, d*1*,... , dn*)= *d* with *q* an attribute in Γ and *d, d*1*,... , dn* ∈ *D*(B), or

⟨−⟩ = *g*( *, d*1*,..., dn*) with *g* a method in Γ and *d*1*,..., dn* ∈ *D*(B).

The intuitive meaning of an atomic Γ-proposition *q*( *, d*1*,..., dn*)= *d* is that we obtain *d* whenever we execute a query *q*( *, d*1*,..., dn*) over the current state. The intuitive meaning of ⟨−⟩ = *g*( *, d*1*,... , dn*) is that there is a state which can be obtained from the current state by applying the method *g* over the current state with the arguments *d*1*,... , dn*.

The linear temporal logic model checker works only if the set of reachable states is finite. The state space generated by the hiddenCCS specification TMR-CCS is infinite. However it can be abstracted and reduced into a finite state space by considering the behavioral equivalences. For instance, we have

such behavioral equivalences for the splitter: rack(rec(initS*,* 1)) ≡ initS and rack(rec(initS*,* 0)) ≡ initS. Similar equivalences are given for the other components.

We verify now the following property: if two modules are working properly, then the voter will select the right value. In order to have a module working properly (without failures), we add the equation get(hop(M)) = vop(get(M)) to its specification. We use the linear temporal logic formula

[] (in-is-eq-0 -> <> (in-is-eq-0 U out-is-eq-0))

expressing that the splitter value (here 0) remains unchanged until the voter outputs it. The state for which we verify the temporal formula is defined as follows:

op initS : -> Splitter . op initM1 : -> Mod1 . op initM2 : -> Mod2 . op initM3 : -> Mod3 . op initV : -> Votter . op init : -> Tmr .

eq init = < initS, initM1, initM2, initM3, initV > .

Then we add to TMR the equations expressing the behavioral equivalences:

vars D1 D2 D3 : Data .

eq rack(rec(initS, 0)) = initS . eq rack(rec(initS, 1)) = initS .

eq put(op(put(initM1, D1)), D2) = put(initM1, D2) . eq put(op(put(initM2, D1)), D2) = put(initM2, D2) . eq put(op(put(initM3, D1)), D2) = put(initM3, D2) .

eq sack(rec(initV, D1, D2, D3)) = initV .

The following two Maude specifications define the predicates and load the model checker.

mod TMR-PREDS is protecting TMR-CCS . including SATISFACTION . subsort CcsTmr < State .

ops out-is-eq-0 in-is-eq-0 : -> Prop . ops out-is-eq-1 in-is-eq-1 : -> Prop . var CT : CcsTmr .

cq CT |= in-is-eq-0 = true if (split(1\* 1\* CT) == 0) . cq CT |= in-is-eq-1 = true if (split(1\* 1\* CT) == 1) . cq CT |= out-is-eq-0 = true if (val(5\* 1\* CT) == 0) . cq CT |= out-is-eq-1 = true if (val(5\* 1\* CT) == 1) .

endm

mod TMR-CHECK is including TMR-PREDS .

including MODEL-CHECKER . including LTL-SIMPLIFIER .

ops initconf : -> CcsTmr .

eq initconf = < init, ’TMR.ProcessId > . endm

Maude provides the following output which express that the property holds:

red modelCheck(initconf, [](in-is-eq-0 -> <> (in-is-eq-0 U out-is-eq-0))) .

Maude> red modelCheck(initconf, [](in-is-eq-0 ->

<>(in-is-eq-0 U out-is-eq-0))) . reduce in TMR-CHECK : modelCheck(initconf, [](in-is-eq-0 ->

<> (in-is-eq-0 U out-is-eq-0))) . rewrites: 5752427265

result Bool: true Maude>

On the contrary, if we consider only one module working properly, then the property does not hold:

Maude>

red modelCheck(initconf, [](in-is-eq-0 -> <>(in-is-eq-0 U out-is-eq-0))) . reduce in TMR-CHECK : modelCheck(initconf, [](in-is-eq-0 ->

<>(in-is-eq-0 U out-is-eq-0))) . rewrites: 900617437

result ModelCheckResult: counterexample({< <initS,initM1,initM2,initM3,...

# Conclusion

The complexity and dynamic interaction of software components provide chal- lenging research issues in large system design and verification. In this paper we investigate the integration between hidden algebra and CCS, using a new specification technique called hiddenCCS. The way we combine process al- gebra CCS used for interaction aspects with hidden algebra used for objects descriptions allows to take advantage of both approaches: high abstraction level, expressiveness, and verification tools. To summarize, in hiddenCCS we use hidden algebra to specify concurrent objects, and CCS to coordinate them by their synchronization and communication elements. A hiddenCCS speci- fication is a triple (B*,* P*,* IC) consisting of an object specification B given in hidden algebra, a CCS description P of the coordinating module, and a set IC of integration consistency requirements. The semantics of hiddenCCS specifi- cations is given by a labeled transition system defined over configurations of form (hidden state, CCS process). We investigate how Maude system is able to describe and verify useful properties of the synchronized and communicat- ing concurrent objects. Maude is used to represent the CCS-based semantics of the synchronized concurrent objects. Since CCS, its Hennessy-Milner logic, and linear temporal logic are implemented in Maude, this system is used to represent the hiddenCCS specifications and their semantics, as well as to ver- ify some properties expressed in linear temporal logics. Rewriting logic is

considered as a logical and semantic framework for object-oriented systems and process calculi of communicating concurrent systems.

A further step is to develop a software tool which automatically builds this rewriting logic specification using the reflection property of the rewriting logic.

The object-oriented features of hidden algebra add a new dimension that is missing in other approaches including LOTOS [[1](#_bookmark6)], a formalism combining a dynamic part based on CCS and CSP with the algebraic specification language ACT ONE. Another formalism with a high level of abstraction is presented in [[15](#_bookmark16)]; it combines CCS with the Common Algebraic Specification Language (CASL). In hiddenCCS we have a clear concern separation that allows a better reuse of the coordination and objects than in [[15](#_bookmark16)].

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