

# Model Checking Reconfigurable Interacting Systems<sup>\*</sup>

Yehia Abd Alrahman, Shaun Azzopardi, and Nir Piterman

University of Gothenburg, Gothenburg, Sweden  
{yehia.abd.alrahman,shaun.azzopardi,nir.piterman}@gu.se

**Abstract.** Reconfigurable multi-agent systems consist of a set of autonomous agents, with integrated interaction capabilities that feature opportunistic interaction. Agents seemingly reconfigure their interaction interfaces by forming collectives, and interact based on mutual interests. Finding ways to design and analyse the behaviour of these systems is a vigorously pursued research goal. We propose a model checker, named R-CHECK<sup>1</sup>, to allow reasoning about these systems both from an individual- and a system- level. R-CHECK also permits reasoning about interaction protocols and joint missions. R-CHECK supports a high-level input language with symbolic semantics, and provides a modelling convenience for interaction features such as reconfiguration, coalition formation, self-organisation, etc.

## 1 Introduction

Reconfigurable Multi-agent systems [20,17], or Reconfigurable MAS for short, have emerged as new computational systems, consisting of a set of autonomous agents that interact based on mutual interest, and thus creating a sort of opportunistic interaction. That is, agents seemingly reconfigure their interaction interfaces and dynamically form groups/collectives based on run-time changes in their execution context. Designing these systems and reasoning about their behaviour is very challenging, due to the high-level of dynamism that Reconfigurable MAS exhibit.

Traditionally, model checking [11,21] is considered as a mainstream verification tool for reactive systems [4] in the community. A system is usually represented by a low-level language such as NuSMV [9], reactive modules [7,16], concurrent game structures [8], and interpreted systems [14]. The modelling primitives of the latter languages are very close to their underlying semantics, e.g., predicate representation, transition systems, etc. Thus, it makes it hard to model and reason about high-level features of Reconfigurable MAS such as reconfiguration, group formation, self-organisation, etc. Indeed, encoding these

---

<sup>\*</sup> This work is funded by the ERC consolidator grant D-SynMA (No. 772459) and the Swedish research council grants: SynTM (No. 2020-03401) and VR project (No. 2020-04963).

<sup>1</sup> Find the associated toolkit repository here: <https://github.com/dsynma/recipe>.

features in existing formalisms would not only make it hard to reason about them, but will also create exponentially large and detailed models that are not amenable to verification. The latter is a classical challenge for model checking and is often termed as *state-space explosion*.

Existing techniques that attempt to tame the state-space explosion problem (such as BDDs, abstraction, bounded model checking, etc.) can only act as a mitigation strategy, but cannot provide the right-level of abstraction to compactly model and reason about high-level features of Reconfigurable MAS.

MAS are often programmed using high-level languages that support domain-specific features of MAS like emergent behaviour [1,22,6], interactions [2], intentions [12], knowledge [14], etc. These descriptions are very involved to be directly encoded in plain transition systems. Thus, we often want programming abstractions that focus on the domain concepts, abstract away from low-level details, and consequently reduce the size of the model under consideration. The rationale is that reasoning about a system requires having the right level of abstraction to represent its behaviour. Thus, there is a pressing demand to extend traditional model checking tools with support for reasoning about high-level features of Reconfigurable MAS. This suggests supporting an intuitive description of programs, actions, protocols, reconfiguration, self-organisation, etc.

RECIPE [3,2] is a promising framework to support modelling and verification of reconfigurable multi-agent system. It is supported with a symbolic semantics and model representation that permits the usage of BDDs to enable efficient analysis. However, writing models in RECIPE is very hard and error prone. This is because RECIPE models are encoded in a predicate-based representation that is far from how we usually program. In fact, the predicate representation of RECIPE supports no programming primitives to control the structure of programs, and thus everything is encoded using state variables.

In this paper, we present R-CHECK, a model checking toolkit for verifying and simulating reconfigurable multi-agent systems. R-CHECK supports a minimalistic high-level programming language with symbolic semantics based on the RECIPE framework. The syntax of the language was first presented briefly, along with a short case study, in [5]. Here we formally present the syntax and semantics of R-CHECK language and we use it to model and reason about a nontrivial case study from the realm of reconfigurable and self-organising MAS. We provide two types of semantics: structural semantics in terms of automata to recover information about interaction actions and message exchange, and an execution semantics based on RECIPE. The interaction information recovered in the structural semantics is recorded succinctly in the execution semantics, and thus permits reasoning about interaction protocols and message exchange.

We integrate R-CHECK with NUXMV and enable LTL symbolic and bounded model checking. This specialised integration provides a powerful tool that permits verifying high-level features of Reconfigurable MAS. Indeed, we can reason about systems both from an individual and a system level. We show how to reason about synchronisations, interaction protocols, joint missions, and how to

express high-level features such as channel mobility, reconfiguration, coalition formation, self-organisation, etc.

The structure of this paper: In Sect. 2, we present a background on RECIPE [3,2], the underlying theory of R-CHECK. In Sect 3, we present the language of R-CHECK and its symbolic semantics. In Sect. 4, we provide a nontrivial case study to model autonomous resource allocation. In Sect. 5 we discuss the integration of R-CHECK with NUXMV and we demonstrate our development using high-level properties. Finally, we report concluding remarks in Sect. 6.

## 2 ReCiPe: a model of computation

We present the underlying theory of R-CHECK. Indeed, R-CHECK accepts a high-level language that is based on the symbolic RECIPE formalism [3,2]. We briefly present RECIPE agents and their composition to generate a system-level behaviour. Formally, agents rely on a set of common variables CV, a set of data variables D, and a set of channels CH containing the broadcast one  $\star$ . Common variables CV are used by agents to send messages that indirectly specify constraints on receivers. That is, each agent has local variables, identified by CV using a re-labelling function. Thus, agents specify constraints anonymously on common variables which are later translated to the corresponding receiver local variables. That is, when the messages are delivered, the receiver re-label CV in the constraints and check their satisfaction; data variables D are the actual communicated values in the message; channels CH define the set of channels that agents use to communicate.

**Definition 1 (Agent).** *An agent is  $A_i = \langle V_i, f_i, g_i^s, g_i^r, \mathcal{T}_i^s, \mathcal{T}_i^r, \theta_i \rangle$ ,*

- $V_i$  is a finite set of typed local variables, each ranging over a finite domain. A state  $s^i$  is an interpretation of  $V_i$ , i.e., if  $\text{Dom}(v)$  is the domain of  $v$ , then  $s^i$  is an element in  $\prod_{v \in V_i} \text{Dom}(v)$ . The set  $V'$  denotes the primed copy of  $V$  and  $\text{ld}_i$  to denote the assertion  $\bigwedge_{v \in V_i} v = v'$ .
- $f_i : \text{CV} \rightarrow V_i$  is a function, associating common variables to local variables. The notation  $f_i$  is used for the assertion  $\bigwedge_{cv \in \text{CV}} cv = f_i(cv)$ .
- $g_i^s(V_i, \text{CH}, \text{D}, \text{CV})$  is a send guard specifying a condition on receivers. That is, the predicate, obtained from  $g_i^s$  after assigning  $s^i$ ,  $ch$ , and  $\mathbf{d}$  (an assignment to D), which is checked against every receiver  $j$  after applying  $f_j$ .
- $g_i^r(V_i, \text{CH})$  is a receive guard describing the connectedness of an agent to a channel  $ch$ . We let  $g_i^r(V_i, \star) = \text{true}$ , i.e., every agent is always connected to the broadcast channel. Note, however, that receiving a broadcast message could have no effect on an agent.
- $\mathcal{T}_i^s(V_i, V'_i, \text{D}, \text{CH})$  is an assertion describing the send transition relation while  $\mathcal{T}_i^r(V_i, V'_i, \text{D}, \text{CH})$  is an assertion describing the receive transition relation. It is assumed that an agent is broadcast input-enabled, i.e.,  $\forall v, \mathbf{d} \exists v' \text{ s.t. } \mathcal{T}_i^r(v, v', \mathbf{d}, \star)$ .
- $\theta_i$  is an assertion on  $V_i$  describing the initial states, i.e., a state is initial if it satisfies  $\theta_i$ .

Agents exchange messages of the form  $m = (ch, \mathbf{d}, i, \pi)$ . A message is defined by the channel it is sent on  $ch$ , the data it carries  $\mathbf{d}$ , the sender identity  $i$ , and the assertion describing the possible local assignments to common variables of receivers  $\pi$ . The predicate  $\pi$  is obtained from  $g_i^s(s^i, ch, \mathbf{d}, CV)$  for an agent  $i$ , where  $s^i \in \prod_{v \in V_i} \text{Dom}(v)$  and  $ch$  and  $\mathbf{d}$  are the channel and assignment in the message.

A set of agents agreeing on common variables  $CV$ , data variables  $D$ , and channels  $CH$  define a *system*. A system is defined as follows.

**Definition 2 (Discrete System).** *Given a set  $\{A_i\}_i$  of agents, a system is defined as follows:  $S = \langle \mathcal{V}, \rho, \theta \rangle$ , where  $\mathcal{V} = \bigsqcup_i V_i$ , a state of the system  $s$  is in*

*$\prod_i \prod_{v \in V_i} \text{Dom}(v)$  and the initial assertion  $\theta = \bigwedge_i \theta_i$ . The transition relation of the system is as follows:*

$$\rho : \exists ch \exists D \bigvee_k \mathcal{T}_k^s(V_k, V'_k, D, ch) \wedge \bigwedge_{j \neq k} \left( \exists CV. f_j \wedge \begin{pmatrix} g_j^r(V_j, ch) \wedge \mathcal{T}_j^r(V_j, V'_j, D, ch) \wedge g_k^s(V_k, ch, D, CV) \\ \vee \\ \neg g_j^r(V_j, ch) \wedge \text{ld}_j \\ \vee \\ ch = \star \wedge \neg g_k^s(V_k, ch, D, CV) \wedge \text{ld}_j \end{pmatrix} \right).$$

The transition relation  $\rho$  describes two modes of interactions: blocking multicast and non-blocking broadcast. Formally,  $\rho$  relates a system state  $s$  to its successors  $s'$  given a message  $m = (ch, \mathbf{d}, k, \pi)$ . Namely, there exists an agent  $k$  that sends a message with data  $\mathbf{d}$  (an assignment to  $D$ ) with assertion  $\pi$  (an assignment to  $g_k^s$ ) on channel  $ch$  and all other agents are either (a) connected to channel  $ch$ , satisfy the send predicate  $\pi$ , and participate in the interaction (i.e., has a corresponding receive transition for the message), (b) not connected and idle, or (c) do not satisfy the send predicate of a broadcast and idle. That is, the agents satisfying  $\pi$  (translated to their local state by the conjunct  $\exists CV. f_j$ ) and connected to channel  $ch$  (i.e.,  $g_j^r(s^j, ch)$ ) get the message and perform a receive transition. As a result of interaction, the state variables of the sender and these receivers might be updated. The agents that are *not connected* to the channel (i.e.,  $\neg g_j^r(s^j, ch)$ ) do not participate in the interaction and stay still. In case of broadcast, namely when sending on  $\star$ , agents are always connected and the set of receivers not satisfying  $\pi$  (translated again as above) stay still. Thus, a blocking multicast arises when a sender is blocked until all *connected* agents satisfy  $\pi \wedge f_j$ . The relation ensures that, when sending on a channel that is different from the broadcast channel  $\star$ , the set of receivers is the full set of *connected* agents. On the broadcast channel agents who do not satisfy the send predicate do not block the sender.

R-CHECK adopts a symbolic model checking approach that directly works on the predicate representation of RECIPE systems. Technically speaking, the behaviour of each agent is represented by a first-order predicate that is defined as a disjunction over the send and the receive transition relations of that agent. Moreover, both send and receive transition relations can be represented by a disjunctive normal form predicate of the form  $\bigvee (\bigwedge_j \text{assertion}_j)$ . That is, a disjunct

of all possible send/receive transitions enabled in each step of a computation. In the following, we will define a high-level language that can be used to write user-friendly programs with symbolic computation steps. We will also show how to translate these programs to RECIPE predicate representation.

### 3 The R-CHECK Language

We formally present the syntax of R-CHECK language and show how to translate it to the RECIPE predicate representation. We start by introducing the type **agent**, its structure, and how to instantiate it; we introduce the syntax of the agent behaviour and how to create a system of agents. The type **agent** is reported in Fig. 1.

```

1  agent name
2  local:
3  var_name:type , ... , var_name:type
4  init:  $\theta_T$ 
5  relabel:
6  common_var <- Exp
7  :
8  common_var <- Exp
9  receive-guard:  $g^r(V_T, CH)$ 
10 repeat: P

```

Fig. 1: Agent type

Intuitively, each agent type has a **name** that identifies a specific type of behaviour. That is, we permit creating multiple instances/copies with the same type of behaviour. Each agent has a local state **local** represented by a set of local variables  $V_T$ , each of which can be of a type boolean, integer or enum. The initial state of an agent **init**:  $\theta_T$  is a predicate characterising the initial assignments to the agent local variables. The section **relabel** is used to implement the relabelling function of common variables in a RECIPE agent. Here, we allow the relabelling to include a binary expression **Exp** over local variables  $V_T$  to accommodate a more expressive relabelling mechanism, e.g.,  $cv_1 \leftarrow (\text{length} \geq 20)$ . The section **receive-guard** specifies the connectedness of the agent to channels given a current assignment to its local variables. The non-terminating behaviour of an agent is represented by **repeat**: P, which executes the process P indefinitely.

Before we introduce the syntax of agent behaviour, we show how to instantiate an agent and how to compose the different agents to create a system. An agent type of name  $A$  can be instantiated as follows  $A(id, \theta)$ . That is, we create an instance of  $A$  with identity  $id$  and an additional initial restriction  $\theta$ . Here, we take the conjunction of  $\theta$  with the predicate in the **init** section of the type  $A$  as the initial condition of this instance. We use the parallel composition operator

$\parallel$  to inductively define a system as in the following production rule.

$$\text{(System)} \quad S ::= A(id, \theta) \mid S_1 \parallel S_2$$

That is, a system is either an instance of agent type or a parallel composition of set of instances of (possibly) different types. The semantics of  $\parallel$  is fully captured by  $\rho$  in Def. 2.

The syntax of an R-CHECK process is inductively defined as follows.

$$\begin{aligned} \text{(Process)} \quad P &::= P;P \mid P+P \mid \text{rep } P \mid C \\ \text{(Command)} \quad C &::= l:C \mid \langle \Phi \rangle ch! \pi \mathbf{d} \mathbf{U} \mid \langle \Phi \rangle ch? \mathbf{U} \end{aligned}$$

A process  $P$  is either a sequential composition of two processes  $P;P$ , a non-deterministic choice between two processes  $P+P$ , a loop  $\text{rep } P$ , or a command  $C$ . There are three types of commands corresponding to either a labelled command, a message-send or a message-receive. A command of the form  $l:C$  is a syntactic labelling and is used to allow the model checker to reason about syntactic elements as we will see later. A command of the form  $\langle \Phi \rangle ch! \pi \mathbf{d} \mathbf{U}$  corresponds to a message-send. Intuitively, the predicate  $\Phi$  is an assertion over the current assignments to local variables, i.e., is a pre-condition that must hold before the transition can be taken. As the names suggest,  $ch$ ,  $\pi$  and (respectively)  $\mathbf{d}$  are the communication channel, the sender predicate, and the assignment to data variables (i.e., the actual content of the message). Lastly,  $\mathbf{U}$  is the next assignment to local variables after taking the transition. We use  $!$  to distinguish send transitions. A command of the form  $\langle \Phi \rangle ch? \mathbf{U}$  corresponds to a message-receive. Differently from message-send, the predicate  $\Phi$  can also predicate on the received values from the incoming message, i.e., the assignment  $\mathbf{d}$ . We use  $?$  to distinguish receive transitions.

Despite the minimalistic syntax of R-CHECK, we can express every control flow structure in a high-level programming language. For instance, by combining non-determinism and pre-conditions of commands, we can encode any structure of IF-Statement. Similarly, we can encode finite loops by combining  $\text{rep } P$  and commands  $C$ , e.g.,  $(\text{rep } C_1 + C_2)$  means: repeat  $C_1$  or block until  $C_2$  happens.

### 3.1 The semantics of R-CHECK

We initially give a structural semantics to R-CHECK process using a finite automaton such that each transition in the automaton corresponds to a symbolic transition. Intuitively, the automaton represents the control structure of an R-CHECK process. We will further use this automaton alongside the agent definition to give an R-CHECK agent an execution semantics based on the symbolic RECIPE framework. This two-step semantics will help us in verifying structural properties about R-CHECK agents.

**Definition 3 (Structure automaton).** *A structure automaton is of the form  $G = \langle S, \Sigma, s_i, E, s_f \rangle$ , where*

- $S$  is a finite set of states;
- $s_i, s_f \in S$ : are two states that, respectively, represent the initial state and the final state in  $G$ ;
- $\Sigma$  is the alphabet of  $G$ ;
- $E \subseteq S \times \Sigma \times S$ : is the set of edges of  $G$ .

We use  $(s_1, \sigma, s_2)$  to denote an edge  $e \in E$  such that  $s_1$  is the source state of  $e$ ,  $s_2$  is the target state of  $e$  and the letter  $\sigma$  is the label of  $e$ .

Now, everything is in place to define the structure semantics of R-CHECK processes. We define a function  $\langle \cdot \rangle^{[s_i, s_f]} : P \rightarrow 2^E$  which takes an R-CHECK process  $P$  as input and produces the set of edges of the corresponding structure automaton. The function  $\langle \cdot \rangle^{[s_i, s_f]}$  assumes that each process has unique initial state  $s_i$  and final state  $s_f$  in the structure automaton. Please note that the states of the structure automaton only represent the control structure of the process, and an agent can have multiple initial states depending on  $\theta_T$  while starting from  $s_i$ . The definition of the translation function  $\langle \cdot \rangle^{[s_i, s_f]}$  is reported below.

$$\begin{aligned}
 \langle \text{repeat} : P \rangle^{[s_i, s_f]} &\triangleq \langle P \rangle^{[s_i, s_i]} \\
 \langle P_1 ; P_2 \rangle^{[s_i, s_f]} &\triangleq \langle P_1 \rangle^{[s_i, s_1]} \cup \langle P_2 \rangle^{[s_1, s_f]} \quad \text{for a fresh } s_1 \\
 \langle P_1 + P_2 \rangle^{[s_i, s_f]} &\triangleq \langle P_1 \rangle^{[s_i, s_f]} \cup \langle P_2 \rangle^{[s_i, s_f]} \\
 \langle \text{rep } P \rangle^{[s_i, s_f]} &\triangleq \langle P \rangle^{[s_i, s_i]} \\
 \langle C \rangle^{[s_i, s_f]} &\triangleq \{(s_i, C, s_f)\}
 \end{aligned}$$

Intuitively, the structure semantics of  $\langle \text{repeat} : P \rangle^{[s_i, s_f]}$  corresponds to a self-loop in the structure automaton (with  $s_i$  as both the source and the target state) and where  $P$  is repeated indefinitely. Moreover, the semantics  $\langle P_1 ; P_2 \rangle^{[s_i, s_f]}$  is the union of the transitions created by  $P_1$  and  $P_2$  while creating a fresh state in the graph  $s_1$  to allow sequentiality, where  $P_1$  starts in  $s_i$  and ends in  $s_1$  and later  $P_2$  continues from  $s_1$  and ends in  $s_f$ . That is, the structure of the process is encoded using an extra memory. Differently, the non-deterministic choice  $\langle P_1 + P_2 \rangle^{[s_i, s_f]}$  does not require extra memory because the execution  $P_1$  and  $P_2$  is independent. The semantics of  $\langle \text{rep } P \rangle^{[s_i, s_f]}$  is similar to  $\langle \text{repeat} : P \rangle^{[s_i, s_f]}$  and is introduced to allow self-looping inside a non-terminating process. Finally, the semantics of a command  $C$  in an R-CHECK process corresponds to an edge  $\{(s_i, C, s_f)\}$  in the structure automaton. This means that the alphabet  $\Sigma$  of the automaton ranges over R-CHECK commands. Note that the translation function is completely syntactic and does not involve evaluation or enumeration of variables, and thus the resulting automaton is symbolic.

To translate an R-CHECK agent into a RECIPE agent, we first introduce the following functions: `typeOf`, `varsOf`, `predOf` and `guardOf` on a command  $C$ . That is, `typeOf(C)` returns the type of a command  $C$  as either ! (send) or ? (receive). For example, the `typeOf(\langle \Phi \rangle ch ! \pi \mathbf{d} \mathbf{U}) = !`. The `varsOf(C)` function returns the set of local variables that are updated in  $C$ , while the function `predOf(C)` returns

the equivalent predicate characterising  $C$  (while excluding the send predicate  $\pi$  in send commands). For instance,  $\text{predOf}(\langle \text{Link} = c \rangle \star !\pi(\text{MSG} := m)[\text{Link} := b])$  is  $(\text{Link} = c) \wedge (\text{ch} = \star) \wedge (\text{MSG} = m) \wedge (\text{Link}' = b)$ . That is, the predicate characterising local variables  $V_T$ , the primed copy  $V_T'$ , the channel  $ch$  and the data variables  $D$ ; and finally  $\text{guardOf}(C)$  returns the send predicate  $\pi$  in a send command and false otherwise.

Moreover, we use  $\text{KEEP}(X)$  to denote that the set of local variables  $X$  is not changed by a transition (either send or receive). More precisely,  $\text{KEEP}(X)$  is equivalent to the assertion  $\bigwedge_{x \in X} x = x'$ , where  $x'$  is the primed copy of  $x$ .

The next definition shows how to construct a **RECIPE** agent from an **R-CHECK** agent with structure semantics interpreted as a structure automaton.

**Definition 4 (from R-CHECK to ReCiPe).** *Given an instance of agent type  $T$  as defined in Fig. 1 with a structure semantics interpreted as a structure automaton  $G = \langle S, \Sigma, s_i, E, s_f \rangle$ , we can construct a **RECIPE** agent  $A = \langle V, f, g^s, g^r, \mathcal{T}^s, \mathcal{T}^r, \theta \rangle$  that implements its behaviour.*

*We construct  $A$  as follows:*

- $V = V_T \cup \{\text{st}\}$ : that is, the union of the set of declared variables  $V_T$  in the *local* section of  $T$  in Fig. 1 and a new state variable  $\text{st}$  ranging over the states  $S$  in  $G$  of the structure automaton, representing the control structure of the process of  $T$ . Namely, the control structure of the behaviour of  $T$  is now encoded as an additional variable in  $A$ ;
- the initial condition  $\theta = \theta_T \wedge (\text{st} = s_i)$ : that is the conjunction of the initial condition  $\theta_T$  in the *init* section of  $T$  in Fig. 1 and the predicate  $\text{st} = s_i$ , specifying the initial state of  $G$ .
- $f$  and  $g^r$  have one-to-one correspondence in section *relabel* and section *receive-guard* respectively of  $T$  in Fig. 1.

$$\begin{aligned}
 - g^s &= \bigvee_{\sigma \in \Sigma: \text{typeOf}(\sigma) = !} \text{guardOf}(\sigma) \\
 - \mathcal{T}^s &= \bigvee_{(s_1, \sigma, s_2) \in E: \text{typeOf}(\sigma) = !} \left( \begin{array}{c} \text{predOf}(\sigma) \wedge (\text{st} = s_1) \wedge (\text{st}' = s_2) \wedge \\ \text{KEEP}(V_T \setminus \text{varsOf}(\sigma)) \end{array} \right) \\
 - \mathcal{T}^r &= \bigvee_{(s_1, \sigma, s_2) \in E: \text{typeOf}(\sigma) = ?} \left( \begin{array}{c} \text{predOf}(\sigma) \wedge (\text{st} = s_1) \wedge (\text{st}' = s_2) \wedge \\ \text{KEEP}(V_T \setminus \text{varsOf}(\sigma)) \end{array} \right).
 \end{aligned}$$

## 4 Case Study: Autonomous resource allocation

We model a scenario where a group of clients are requested to jointly solve a problem. Each client will buy a computing virtual machine (VM) from a resource manager and use it to solve its task. Initially, clients know the communication link of the manager, but they need to self-organise and coordinate the use of the link anonymously. The manager will help establishing connections between clients and available machines, and later clients proceed interacting independently with machines on private links learnt when the connection is established.

There are two types of machines: high performance machines and standard ones. The resource manager commits to provide high performance VMs to clients,



but when all of these machines are reserved, the clients are assigned to standard ones. The protocol proceeds until each client buys a machine, and then all clients have to collaborate to solve the problem and complete the task.

A client uses the local variables `cLink`, `mLink`, `tLink`, `role` to control its behaviour, where `cLink` stores a common link (i.e., the link to interact with the resource manager), `mLink` is a placeholder for a mobile link that can be learnt at run-time, `tLink` is a link to synchronise with other clients to complete the task, and `role` is the role of the client. The initial condition  $\theta_c$  of a client is:

$$\theta_c : \text{cLink} = c \wedge \text{mLink} = \text{empty} \wedge \text{tLink} = t \wedge \text{role} = \text{client},$$

specifying that the resource manager is reachable on `c`, the mobile link is empty, the task link is `t` and the role is `client`.

Note that the interfaces of agents are parameterised to their local states and state changes may create dynamic and opportunistic interactions. For instance, when `cLink` is set to `empty`, the client discards all messages on `c`; also when a channel is assigned to `mLink`, the client starts receiving messages on that channel.

Clients may use broadcast or multicast; in a broadcast, receivers (if exist) may anonymously receive the message when they are interested in its values (and when they satisfy the send predicate). Otherwise, an agent may not participate in the interaction. In multicast, all agents listening on the multicast channel must participate to enable the interaction.

Broadcast is used when agents are unaware of the existence of each other while (possibly) sharing some resources while multicast is used to capture a more structured interaction where agents have dedicated links to interact. In our example, clients are not aware of the existence of each other while they share the resource manager channel `c`. Thus they may coordinate to use the channel anonymously by means of broadcast. A client reserves the channel `c` by means of a broadcast message with a predicate targeting other clients. All other clients self-organise and disconnect from `c` and wait for a release message.

A message in R-CHECK carries an assignment to a set of data variables  $D$ . In our scenario,  $D = \{\text{LNK}, \text{MSG}\}$  where `LNK` is used to exchange a link with other agents, and `MSG` denotes the label of the message and takes values from:

reserve, request, release, buy, connect, full, complete.

Agents in this scenario use one common variable `cv` ranging over roles to specify potential receivers. Remember that every agent  $i$  has a relabelling function  $f_i : CV \rightarrow V_i$  that is applied to the send guard once a message is delivered to check whether it is eligible to receive. For a client,  $f_c(\text{cv}) = \text{role}$ . The send guard of a client appears in the messages that the client sends, and we will explain later. In general, broadcasts are destined to agents assigning to the common variable `cv` a value matching the `role` of the sender, i.e, `client`; messages on `cLink` are destined to agents assigning `mgr` to `cv`; and other messages are destined to everyone listening on the right channel.

The receive guard is:  $g_c^r : (\text{ch} = \star) \vee (\text{ch} = \text{cLink}) \vee (\text{ch} = \text{tLink})$ . That is, reception is always enabled on broadcast and on a channel that matches the value

of `cLink` or `tLink`. Note that these guards are parameterised to local variables and thus may change at run-time, creating a dynamic communication structure.

The behaviour of the client is reported in Fig. 2 below:

```

1  repeat: (
2    (sReserve: <cLink==c > *! (cv==role)(MSG := reserve)[]
3    +
4    rReserve: <cLink==c && MSG == reserve> *? [cLink := empty]
5    )
6    ;
7    (
8    sRequest: <cLink!=empty> cLink! (cv==mgr)(MSG := request)[];
9
10   rConnect: <mLink==empty && MSG == connect> cLink? [mLink := LNK];
11
12   sRelease: <TRUE> *! (cv==role)(MSG := release)[cLink := empty];
13
14   sBuy: <mLink!=empty> mLink! (TRUE)(MSG := buy)[mLink := empty];
15   (
16     sSolve: <TRUE> tLink!(TRUE)(MSG := complete)[]
17     +
18     <MSG == complete> tLink? []
19   )
20   +
21   rRelease: <cLink==empty && MSG == release> *? [cLink := c]
22   )
23 )

```

Fig. 2: Client Behaviour

In this example, we label each command with a name identifying the message and its type (i.e., `s` for send and `r` for receive). For instance, the send transition at Line 2 is labelled with `sReserve` while the receive transition at Line 4 is labelled with `rReserve`. We use these later to reason about agent interactions syntactically.

Initially in Lines 2 – 5, every client may either broadcast a `reserve` message to all other clients (i.e.,  $(cv = role)$ ) or receive a `reserve` message from one of them. This is to allow clients to self-organise and coordinate to use the common link. That is, a client may initially reserve an interaction session with the resource manager by broadcasting a `reserve` message to all other clients, asking them to disconnect the common link  $c$  (stored in their local variable `cLink`); or receive a `reserve` message, i.e., gets asked by another client to disconnect channel  $c$ . In either case, the client progress to Line 7. Depending on what happened in the previous step, the client may proceed to establish a session with the resource manager (i.e.,  $(cv = mgr)$ ) and a machine (Lines 8 – 19) or gets stuck waiting for a `release` message from the client, currently holding the session (Line 21). In the latter case, the client gets back in the loop to (Line 1) after receiving a `release` message and attempts again to establish the session.

In the former case, the client uses the blocking multicast channel `c` to send a request to the resource manager (Line 8) and waits to receive a private connection link with a virtual machine agent on `cLink` (Line 10). When the client receives the `connect` message on `cLink`, the client assigns its `mLink` variable the value of

LNK in the message. That is, the client is now ready to communicate on `mLink`. On Line 12, the agent releases the common link `c` by broadcasting a `release` message to all other clients (with `cv = role`) and proceeds to Line 14 and starts communicating privately with the assigned VM agent. The client buys a service from the VM agent on a dedicated link stored in `mLink` by sending a `buy` to the VM agent to complete the transaction. The client proceeds to line 15 and wait for other clients to collaborate and finish the task. Thus, the client either initiates the last step and sends a `complete` message when the rest of clients are ready (Line 16) or receives a `complete` message from another client that is ready.

We may now specify the manager and the virtual machine behaviour, and show how reconfigurable multicast can be used to model a point-to-point interaction in a clean way.

The resource manager has the following local variables:

$$\text{hLink, sLink, cLink, role}$$

where `hLink` and `sLink` store channel names to communicate with high- and standard-performance VMs respectively and the rest are as defined before.

The initial condition is:

$$\theta_m : \text{hLink} = g_1 \wedge \text{sLink} = g_2 \wedge \text{cLink} = c \wedge \text{role} = \text{mgr}.$$

Note that the link  $g_1$  is used to communicate with the group of high performance machines while  $g_2$  is used for standard ones.

The send guard for a manager is always satisfied, (i.e.,  $g_m^s$  is `true`) while the receive guard specifies that a manager only receives broadcasts or on channels that match with `cLink` or `hLink`, i.e.,  $g_m^r$  is  $(\text{ch} = \star) \vee (\text{ch} = \text{cLink}) \vee (\text{ch} = \text{hLink})$ .

The behaviour of the agent manager is reported in Fig. 3 below:

```

1  repeat: (
2      rRequest: <MSG == request> cLink? [];
3      sForward: <TRUE> hLink! (TRUE)(MSG := request)[];
4      (
5          rConnect: <MSG == connect> cLink? []
6          +
7          rep ( rFull: <MSG == full> hLink? [];
8              sRequest: <TRUE> sLink! (TRUE)(MSG := request)[]
9          )
10     )
11 )

```

Fig. 3: Manager Behaviour

In summary, the manager initially forwards requests received on channel `c` (Line 2) to the high performance VMs first as in (Line 3). The negotiation protocol with machines is reported in Lines 5 – 9. The manager can receive a `connect` message and directly enable the client to connect with the virtual machine as in (Line 5) or receive a `full` message, informing that all high performance machines

are fully occupied. In the latter case, the requests are forwarded to the standard performance machines on `sLink` as in (Lines 7 – 9). The process repeats until a `connect` message is received (Line 5) and the manager gets back to (Line 1) to handle other requests. Clearly, the specifications of the manager assumes that there are a plenty of standard VMs and a limited number of high performance ones. Thus it only expects a `full` message to be received on channel `hLink`. Note also that the manager gets ready to handle the next request once a `connect` message (`connect`) is received on channel `c` and leaves the client and the selected VM to interact independently.

The virtual machine has the following local variables:

`gLink, pLink, cLink, asgn`

where `asgn` indicates if the VM is assigned, `gLink` is a group link, `pLink` is a private link and the rest is as before; apart from `gLink` and `pLink`, which are machine dependent, the initial condition is of the form:

$$\theta_{vm} : \neg asgn \wedge cLink = \text{empty}$$

where initially virtual machines are not listening on the common link `cLink`. Depending on the group that the machine belong to, the `gLink` will either be assigned to high performance machine group `g1` or the standard one `g2`. Moreover, each machine has a unique private link `pLink`. The send guard for a VM is always satisfied, (i.e.,  $g_{mv}^s$  is `true`) while the receive guard specifies that a VM always receives on broadcast, `pLink`, `gLink` and `cLink`, i.e.,

$$g_{vm}^r : ch = \star \vee ch = gLink \vee ch = pLink \vee ch = cLink.$$

The behaviour of the virtual machine agent is reported in Fig. 4:

```

1  repeat: (
2      rForward: <cLink==empty && MSG == request> gLink? [cLink:= c];
3      (
4          sConnect: <cLink==c && !asgn> cLink! (TRUE)(MSG := connect, LNK := pLink)
          [cLink:= empty, asgn:= TRUE]
5          +
6          sFull: <cLink==c && asgn> gLink! (TRUE)(MSG := full)[cLink:= empty]
7          +
8          rConnect: <cLink==c && MSG == connect> cLink? [cLink:= empty]
9          +
10         rFull: <cLink==c && asgn && MSG == full> gLink? [cLink:= empty]
11         )
12         +
13         rBuy: <MSG == buy> pLink? []
14     )

```

Fig. 4: Machine Behaviour

Intuitively, a VM either receives the forwarded request on the group channel `gLink` (Line 2) and thus activating the common link and also a nondeterministic

choice between `connect` and `full` messages (Lines 3–11) or receives a `buy` message from a client on the private link `pLink`. In the latter case, the VM agent agrees to sell the service and stays idle. In the former case, a VM sends `connect` with its private link `pLink` carried on the data variable `LNK` and send it on `cLink` if it is not assigned or sends `full` on `gLink` otherwise. Note that `full` message can only go through if all VMs in group `gLink` are assigned. Note that reception on `gLink` is always enabled by the receive guard  $g_{vm}^r$  and the receive transition at Line 10 specifies that a machine enables a send on a `full` message only when it is assigned. For example, if `gLink = g1` then only when all machines in group  $g_1$  are assigned, a `full` message can be enabled.

Furthermore, a `connect` message will also be received by other VMs in the group `gLink` (Line 8). As a result, all other available VMs (i.e.,  $\neg\text{asgn}$ ) in the same group do not reply to the request. Thus, one VM is non-deterministically selected to provide a service and a point-to-point like interaction is achieved. Note that this easy encoding is possible because agents change communication interfaces dynamically by enabling and disabling channels.

Now, we can easily create an R-CHECK system as follows.

$$\begin{aligned}
 \text{system} = & \text{Client}(\text{client1}, \text{TRUE}) \parallel \text{Client}(\text{client2}, \text{TRUE}) \\
 & \parallel \text{Client}(\text{client3}, \text{TRUE}) \parallel \text{Manager}(\text{manager}, \text{TRUE}) \\
 & \parallel \text{Machine}(\text{machine1}, \text{gLink} = \text{g1} \wedge \text{pLink} = \text{vmm1}) \\
 & \parallel \text{Machine}(\text{machine2}, \text{gLink} = \text{g1} \wedge \text{pLink} = \text{vmm2}) \\
 & \parallel \text{Machine}(\text{machine3}, \text{gLink} = \text{g2} \wedge \text{pLink} = \text{vmm3})
 \end{aligned} \tag{1}$$

This system is the parallel composition (according to Def. 2) of three copies of a client  $\{\text{client}_1, \dots, \text{client}_3\}$ ; a copy of a manager  $\{\text{manager}\}$ ; and finally three copies of a machine  $\{\text{machine}_1, \dots, \text{machine}_3\}$ , each belongs to a specific group and a private link. For instance, `machine1` belongs to group  $g_1$  (the high performance machines) and has a private link named `vmm1`.

## 5 Model-checking through nuXmv

We describe the integration of R-CHECK with the NUXMV model checker [10] to enable an enhanced symbolic LTL model-checking. We also demonstrate our developments using examples. We will show how the combined features of R-CHECK, the symbolic LTL model-checking, and NUXMV provides a powerful tool to verify high-level features of reconfigurable and interactive systems.

**From R-CHECK to nuXmv** We give individual R-CHECK agents a symbolic semantics based on the RECIPE framework as shown in Sect. 3.1 and Def. 4. Notably, we preserve the labels of commands (i.e.,  $l : \sigma$ ) and use them as subpredicate definitions. For instance, given a labeled edge  $(s_1, l : \sigma, s_2)$  in the structure automaton  $G$  in Def. 3, we translate it into the following predicate in RECIPE as explained in Def. 4:

$$l := \text{predOf}(\sigma) \wedge (\text{st} = s_1) \wedge (\text{st}' = s_2) \wedge \text{KEEP}(V_T \setminus \text{varsOf}(\sigma)).$$

The only difference here is that the label  $l$  is now a predicate definition and its truth value defines if the transition  $(s_1, l : \sigma, s_2)$  is feasible. Since every command is translated to either message-send or message-receive, we can use these labels now to refer to message exchange syntactically inside LTL formulas.

Moreover, we rename all local variables of agents to consider the identity of the agent as follows: for example, given the `cLink` variable of a client, we generate the variable `client - cLink`. This is important when different agents use the same identifier for local variables. We also treat all data variables `D` and channel names `CH` as constants and we construct a RECIPE system  $S = \langle \mathcal{V}, \rho, \theta \rangle$  as defined in Def. 2 while considering subpredicate definitions and agent variables after renaming. Technically, a RECIPE system  $S$  has a one-to-one correspondence to a NUXMV module  $M$ . That is, both  $S$  and  $M$  agrees on local variables  $\mathcal{V}$  and the initial condition  $\theta$ , but are slightly different with respect to transition relations. Indeed, the transition relation  $\rho$  of  $S$  as defined in Def. 2 is translated to an equivalent transition relation  $\hat{\rho}$  of  $M$  as follows:

$$\hat{\rho} = \rho \vee (\neg\rho \wedge \text{KEEP}(\mathcal{V})).$$

That is, NUXMV translates deadlock states in  $S$  into stuttering (sink) states in  $M$  where system variables do not change.

R-CHECK provides an interactive simulator that allows the user to simulate the system either randomly or based on predicates that the user supplies. For instance, starting from some state in the simulation, the user may supply the constraint `next(client1-cLink) = c` to ask the simulator to select the transition that leads to a state where the next value of `client1-cLink` equals `c`. If such constraint is feasible (i.e., there exists a transition satisfying the constraint), the simulator selects such transition, and otherwise it returns an error message. Users can also refer to message -send and -receive using command labels in the same way. A constraint on a send transition like `client1-sReserve`, to denote the sending of the message `reserve` in Fig. 2, Line 2, means that this transition is feasible in the current state of simulation. However, a constraint on a receive transition `client-rReserve`, like on the message in Fig. 2, Line 4, means that this transition is already taken from the previous state of simulation. This slight difference between send and receive transitions is due to the fact that receive transitions cannot happen independently and only happen due to a joint send transition. Finally, R-CHECK is supported with an editor, syntax highlighting and visualising tool. For instance, once the model of the scenario in Sect. 4 is compiled, R-CHECK produces the corresponding labelled and symbolic structure automata in Fig. 5, which the user may use to reason about interactions.

**Symbolic Model Checking** R-CHECK supports both symbolic LTL model checking and bounded LTL model checking. We illustrate the capabilities of R-CHECK by several examples. In this section, we will use Eq. 1, Sect. 4 and the corresponding structure automata in Fig. 5 as the system under consideration.

We show how to verify properties about agents both from individual and interaction protocols level by predicating on message exchange rather than on

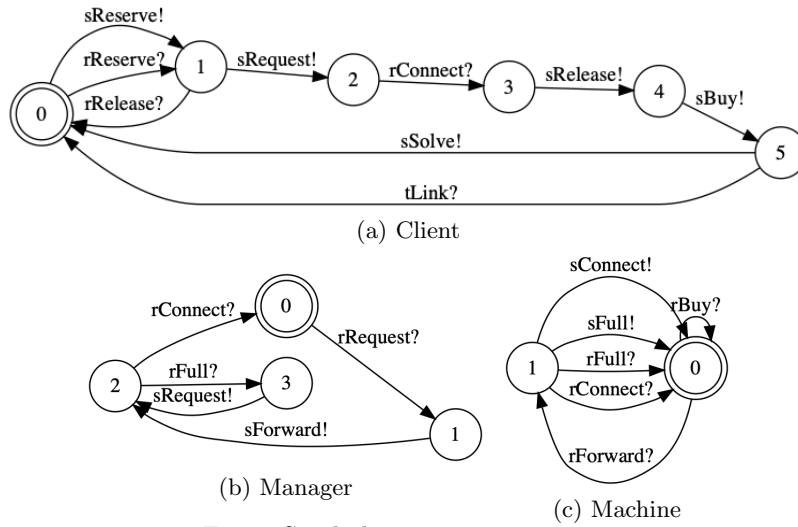


Fig. 5: Symbolic structure automata

atomic propositions. It should be noted that the transition labels in Fig. 5 are not mere labels, but rather predicates with truth values changing dynamically at run-time, introducing opportunistic interaction. For instance, we can reason about a client and its connection to the system as follows.

$$\begin{aligned}
 &G (\text{client1-sReserve} \rightarrow F \text{client1-sRequest}) \quad (1) \\
 &G (\text{client1-sReserve} \rightarrow F \text{client1-sRelease}) \quad (2) \\
 &G (\text{client1-sRequest} \rightarrow F \text{client1-rConnect}) \quad (3)
 \end{aligned}$$

The liveness condition (1) specifies that the client can send a request to the manager after it has already reserved the common link  $c$ ; the liveness condition (2) specifies that the client does not hold a live lock on the common link  $c$ . Namely, the client releases the common link eventually. The liveness condition (3) specifies that the *system* is responsive, i.e., after the client's request, other agents collaborate to eventually supply a connection.

We can also reason about synchronisation and reconfiguration in relation to local state as in the following.

$$\begin{aligned}
 &G (\text{manager-sForward} \rightarrow X \text{machine1-rForward}) \quad (4) \\
 &F (\text{client1-sRelease} \ \& \ G(\text{!client1-rConnect})) \quad (5) \\
 &G (\text{!machine1-asgn} \ \& \ \text{machine1-rForward}) \rightarrow \text{machine1-sConnect}) \quad (6)
 \end{aligned}$$

In (4), we refer to synchronisation, i.e., the manager has to forward the request before the machine can receive it. Note that this formula does not hold for  $\text{machine}_3$  because  $\text{sForward}$  is destined for group  $g_1$ ; we can refer to reconfiguration in (5), i.e., eventually the client disconnects from the common link  $c$ , and it can never be able to receive connection on that link; moreover, in (6) the

machine sends a connection predicated on its local state, i.e., if it is not assigned. Note that (6) does not hold because `machine1` might lose the race for `machine2` in group `g1` to execute `connect` message.

We can also specify channel mobility and joint missions from a declarative and centralised point of view, as follows.

$$\begin{aligned} & F(\text{client1-mLink} \neq \text{empty}) \ \& \\ & \quad F(\text{client2-mLink} \neq \text{empty}) \ \& \\ & \quad \quad F(\text{client3-mLink} \neq \text{empty}) \longrightarrow \\ & \quad \quad \quad F(\text{client1-sSolve} \mid \text{client2-sSolve} \mid \text{client3-sSolve}) \end{aligned}$$

That is, every client will eventually receive a mobile link (i.e., its `mLink`  $\neq$  `empty`) where it will use this private link to buy a VM, and eventually one client will initiate the termination of the mission by synchronising with the other clients to solve the joint problem.

We are unaware of a model-checker that enables reasoning at such a high-level. The full tool support and all examples in this paper are attached to the submission as supplementary material.

## 6 Concluding Remarks

We introduced the R-CHECK model checking toolkit for verifying and simulating reconfigurable multi-agent system. We formally presented the syntax and semantics of R-CHECK language in relation to the RECIPE framework [3,2], and we used it to model and reason about a nontrivial case study from the realm of reconfigurable and self-organising MAS. Our semantics approach consisted of two types of semantics: structural semantics in terms of automata to recover information about interaction features, and execution semantics based on RECIPE. The interaction information recovered in the structural semantics is recorded succinctly in the execution one, and thus permits reasoning about interaction protocols and message exchange. R-CHECK is supported with a command line tool, a web editor with syntax highlighting and visualisation.

We integrated R-CHECK with NUXMV to enable LTL verification through symbolic, bounded, and IC3 model checking. We showed that this specialised integration provides a powerful tool that permits verifying high-level features such as synchronisations, interaction protocols, joint missions, channel mobility, reconfiguration, self-organisation, etc.

**Related works.** We report on closely related model-checking toolkits and their relation to R-CHECK.

MCMAS is a successful model checker that is used to reason about multi-agent systems and supports a range of temporal and epistemic logic operators. MCMAS is also supported with ISPL, a high-level input language with semantics based on *Interpreted Systems* [14]. The key differences with respect to R-CHECK are: (1) MCMAS models are enumerative and are exponentially



larger than R-CHECK ones; (2) actions in MCMAS are merely synchronisation labels while command labels in R-CHECK are predicates with truth values changing dynamically at run-time, introducing opportunistic interaction; (3) lastly and most importantly R-CHECK is able to model and reason about dynamic communication structure with message exchange and channel mobility while in MCMAS the structure is fixed.

MTSA toolkit [13] is used to reason about labelled transition systems (LTS) and their composition according to the simple multiway synchronisation of Hoare's CSP calculus [18]. MTSA uses *Fluent Linear Temporal logic (FLTL)* [15] to reason about actions, where a fluent is a predicate indicating the beginning and the end of an action. As the case of MCMAS, the communication structure is fixed and there is no way to reason about reconfiguration or even message exchange.

SPIN [19] is originally designed to reason about concurrent systems and protocol design. Although SPIN is successful in reasoning about static coordination protocols, it did not expand its coverage to multi-agent system features. Indeed, the kind of protocols that SPIN can be used to reason about are mainly related to static structured systems like hardware and electronic circuits.

Finally, NUXMV [10] is designed at the semantic level of transition systems. NUXMV implements a large number of efficient algorithms for verification. This makes NUXMV an excellent candidate to serve as a backbone for special-purpose model checking tools. For this reason, we integrate R-CHECK with NUXMV.

**Future works.** We plan to integrate LTOL, from [3], to R-CHECK. Indeed, the authors in [3] provide a PSPACE algorithm for LTOL model checking (improved from EXPSPACE in [2]). This way, we would not only be able to refer to message exchange in logical formulas, but also to identify the intentions of agents in the interaction and characterise potential interacting partners.

Moreover, we would like to equip R-CHECK with a richer specification language that allows reasoning about the knowledge of agents and the dissemination of knowledge in distributed settings. For this purpose, we will investigate the possible integration of R-CHECK with MCMAS [21] to make use of the specialised symbolic algorithms that are introduced for knowledge reasoning.

## References

1. Abd Alrahman, Y., De Nicola, R., Loreti, M.: A calculus for collective-adaptive systems and its behavioural theory. *Inf. Comput.* **268** (2019). <https://doi.org/10.1016/j.ic.2019.104457>
2. Abd Alrahman, Y., Perelli, G., Piterman, N.: Reconfigurable interaction for MAS modelling. In: Seghrouchni, A.E.F., Sukthankar, G., An, B., Yorke-Smith, N. (eds.) *Proceedings of the 19th International Conference on Autonomous Agents and Multiagent Systems, AAMAS '20, Auckland, New Zealand, May 9-13, 2020*. pp. 7–15. International Foundation for Autonomous Agents and Multiagent Systems (2020)
3. Abd Alrahman, Y., Piterman, N.: Modelling and verification of reconfigurable multi-agent systems. *Auton. Agents Multi Agent Syst.* **35**(2), 47 (2021). <https://doi.org/10.1007/s10458-021-09521-x>

4. Aceto, L., Ingólfssdóttir, A., Larsen, K.G., Srba, J.: *Reactive Systems: Modelling, Specification and Verification*. Cambridge University Press (2007). <https://doi.org/10.1017/CBO9780511814105>
5. Alrahman, Y.A., Azzopardi, S., Piterman, N.: R-check: A model checker for verifying reconfigurable mas. In: *International Conference on Autonomous Agents and Multiagent Systems (AAMAS)* (2022)
6. Alrahman, Y.A., Nicola, R.D., Loreti, M.: Programming interactions in collective adaptive systems by relying on attribute-based communication. *Sci. Comput. Program.* **192**, 102428 (2020). <https://doi.org/10.1016/j.scico.2020.102428>
7. Alur, R., Henzinger, T.: *Reactive Modules*. *Formal Methods in System Design* **15**(1), 7–48 (1999)
8. Alur, R., Henzinger, T., Kupferman, O.: Alternating-time temporal logic. *J. ACM* **49**(5), 672–713 (2002). <https://doi.org/10.1145/585265.585270>
9. Cimatti, A., Clarke, E.M., Giunchiglia, E., Giunchiglia, F., Pistore, M., Roveri, M., Sebastiani, R., Tacchella, A.: Nusmv 2: An opensource tool for symbolic model checking. In: Brinksma, E., Larsen, K.G. (eds.) *Computer Aided Verification, 14th International Conference, CAV 2002, Copenhagen, Denmark, July 27-31, 2002, Proceedings*. *Lecture Notes in Computer Science*, vol. 2404, pp. 359–364. Springer (2002). [https://doi.org/10.1007/3-540-45657-0\\_29](https://doi.org/10.1007/3-540-45657-0_29)
10. Cimatti, A., Griggio, A.: Software model checking via IC3. In: Madhusudan, P., Seshia, S.A. (eds.) *Computer Aided Verification - 24th International Conference, CAV 2012, Berkeley, CA, USA, July 7-13, 2012 Proceedings*. *Lecture Notes in Computer Science*, vol. 7358, pp. 277–293. Springer (2012). [https://doi.org/10.1007/978-3-642-31424-7\\_23](https://doi.org/10.1007/978-3-642-31424-7_23)
11. Clarke, E.M., Grumberg, O., Peled, D.A.: *Model Checking*. MIT Press, Cambridge, MA, USA (2000)
12. Cohen, P.R., Levesque, H.J.: Intention is choice with commitment. *Artif. Intell.* **42**(2-3), 213–261 (1990). [https://doi.org/10.1016/0004-3702\(90\)90055-5](https://doi.org/10.1016/0004-3702(90)90055-5)
13. D’Ippolito, N., Fischbein, D., Chechik, M., Uchitel, S.: MTSA: the modal transition system analyser. In: *23rd IEEE/ACM International Conference on Automated Software Engineering (ASE 2008)*, 15-19 September 2008, L’Aquila, Italy. pp. 475–476. IEEE Computer Society (2008). <https://doi.org/10.1109/ASE.2008.78>
14. Fagin, R., Halpern, J., Moses, Y., Vardi, M.Y.: *Reasoning about Knowledge*. MIT Press (1995)
15. Giannakopoulou, D., Magee, J.: Fluent model checking for event-based systems. In: *Proceedings of the 9th European software engineering and 11th ACM SIGSOFT international symposium on Foundations of software engineering*. pp. 257–266. ACM (2003)
16. Gutierrez, J., Harrenstein, P., Wooldridge, M.: From Model Checking to Equilibrium Checking: Reactive Modules for Rational Verification. *Artif. Intell.* **248**, 123–157 (2017). <https://doi.org/10.1016/j.artint.2017.04.003>
17. Hannebauer, M.: *Autonomous Dynamic Reconfiguration in Multi-Agent Systems, Improving the Quality and Efficiency of Collaborative Problem Solving*, *Lecture Notes in Computer Science*, vol. 2427. Springer (2002). <https://doi.org/10.1007/3-540-45834-4>
18. Hoare, C.A.R.: Communicating sequential processes. In: Jones, C.B., Misra, J. (eds.) *Theories of Programming: The Life and Works of Tony Hoare*, pp. 157–186. ACM / Morgan & Claypool (2021). <https://doi.org/10.1145/3477355.3477364>
19. Holzmann, G.J.: The model checker spin. *IEEE Transactions on software engineering* **23**(5), 279–295 (1997)

20. Huang, X., Chen, Q., Meng, J., Su, K.: Reconfigurability in reactive multiagent systems. In: Kambhampati, S. (ed.) Proceedings of the Twenty-Fifth International Joint Conference on Artificial Intelligence, IJCAI 2016, New York, NY, USA, 9-15 July 2016. pp. 315–321. IJCAI/AAAI Press (2016), <http://www.ijcai.org/Abstract/16/052>
21. Lomuscio, A., Qu, H., Raimondi, F.: MCMAS: an open-source model checker for the verification of multi-agent systems. *STTT* **19**(1), 9–30 (2017)
22. Wooldridge, M.J.: An Introduction to MultiAgent Systems, Second Edition. Wiley (2009)