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Distributed Model Checking of Actor Models

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Abstract: Model checking temporal properties is often reduced to finding accepting cycles in Büchi automata. A key ingredient for an effective distributed model checking technique is a distribution policy that does not split the potential accepting cycles of the corresponding automaton among several nodes. In this paper, we introduce a distribution policy to reduce the number of split cycles. This policy is based on the call dependency graph, obtained from the message passing skeleton of the model. We prove theoretical results about the correspondence between the cycles of the call dependency graph and the cycles of the concrete state space and provide empirical data obtained from applying our distribution policy in state space generation and reachability analysis. We take Rebeca, an imperative interpretation of actors, as our modeling language and implement the introduced policy in its distributed state space generator. Our technique can be applied to other message-driven actor-based models where concurrent objects or services are units of concurrency.

Keywords: Distributed Model Checking, State Distribution Policy, Concurrent Objects, Actors, Rebeca

1 Introduction

Providing quality guarantees despite the ever-increasing complexity of computer systems has been and remains a grand challenge. Using formal methods, in general, and model checking [CES86] in particular, has been advocated as a response to this grand challenge. Model-checking tools explore the state space of the system exhaustively to make sure that a given property holds in all possible execution of a system. A major limiting factor in applying model checkers to practical systems is the huge amount of space and time required to store and explore the state space. Generating the state space of large-scale practical systems undoubtedly results in state spaces that cannot fit in the memory of a single computer.

Besides the traditional model-checking reduction techniques, distributed LTL model checking [GMS13, BHR13, VVFB11, BBC05, BBS01, BC06, BCMS06] is a well-known technique to

deal with huge state spaces. In distributed LTL model checking the state space is partitioned into some slices and each slice is assigned to a node. Theoretically, dividing cycle detection in a state space among a number of nodes increases the efficiency of model checking; however, unlike the sequential and the shared-memory parallel algorithms, the efficiency of these algorithms depends on the communication costs [OPE05]. The communication cost directly relates to the distribution policy of states among nodes, as detecting accepting cycles that span over many different nodes requires communication. Another, more fine-grained, representative of communication cost is the number of split transitions; a split transition is a transition between two states, where the hosts of source and destination states are different nodes.

In the present work, we tackle the state distribution policy problem in the state space generation of actor models [Hew72]. We introduce a new state distribution policy based on the the so-called Call Dependency Graph (CDG) of actor models. A CDG represents the abstract causality relation among messages of actors (Section 2). Our abstraction is akin to the dynamic representation of actor's event activation causality proposed by Clinger [Cli81].

The most primitive and widely used distribution policy is random state distribution [GMS13, BHR13, VVFB11, BCMS06]. Random state distribution policy distributes states among nodes based on their hash values. Random distribution policy guarantees load balancing. However, it is not an effective technique as cycles are scattered over many different nodes. In [BBC05], state distribution is performed based on the Büchi automata of the properties. LTL model checkers find accepting cycles in the synchronous product of the state space and the Büchi automata of LTL specifications. Therefore, distributing states based on the strongly connected components of the property Büchi automata avoids creation of split cycles in the state space. This way, there is no need for communication among nodes for detecting accepting cycles. In practice, the corresponding Büchi automata of LTL properties do not have many strongly connected components. Hence, this approach does not work efficiently in most practical cases.

In [OPE05], another state space distribution policy is suggested to improve the locality of cycles. This policy is based on the static analysis of an abstracted model and detects *may* or *must* transition relations among states [LT88]. Based on this analysis, if two states have a *must* relation, they should be stored in a same node. We use a similar idea in our state distribution policy and show that using the CDG improves the locality of cycles by reducing the split transitions in the state space. In other words, we find the *must* relations among the states of actor models using the CDG. Our technique is applicable to other service-oriented models where the unit of concurrency can be modeled as an autonomous active object and message passing is the only way of communication. To illustrate the applicability of our method, we implement it in the distributed model checker of Rebeca, which is an actor-based language for modeling and model checking of reactive systems (Section 3). The experimental results of using CDG illustrate that the number of split transitions is reduced significantly by up to 50% (Section 4). We also discuss possible extensions of our work and possible application domains for it (Section 5).

In a nutshell, the contributions of this paper are as follows:

- Introducing the notion of call dependency graph (CDG) for actor models as an abstract representation for message passing causality (Section 2),
- presenting the relation between the cycles in the CDG and the cycles in the state space of a model (Section 2),

- adapting the notion of CDG in order to define a state distribution policy (Section 3),
- implementing the proposed techniques in a distributed model checking tool (Section 4), and
- providing experimental results and measuring the efficiency of our technique by means of a number of case studies (Section 4).

2 Call Dependency Graphs of Actor Models

The actor model [Hew72, AMST97] is a well-established paradigm for modeling distributed and asynchronous systems. In this model, actors encapsulate the concept of concurrent behavior. Each actor provides services that can be requested by other actors through sending messages to the provider. Messages are put in the message buffer of the receiver; the receiver takes the message and executes the requested service, and consequently, may send some messages to other actors. The source code of a simple actor model is shown in Figure 1. This model consists of two actors ac_1 and ac_2 , each of which provides two services. To start the execution of the model, some messages must be put in the message buffer of the actors (i.e., initially sent messages); this is specified in the `main` block (line 24). Sending a message is denoted by “`actor_name.service_name()`” (line 3).

We illustrate our approach using a Simple Actor Modeling language, called *SAM*, which contains the key features of the actor model. Below, we briefly introduce SAM, which is inspired by the earlier actor models, e.g., by Agha et al. in [AMST97] and by Sirjani et al. in [SMSB04].

Definition 1 (An Actor Model) An actor in SAM is a member of type $Actor = ID \times \mathcal{P}(Vars) \times \mathcal{P}(mtds)$, where $\mathcal{P}(\cdot)$ denotes power set and:

- ID is the set of actor identifiers,

```

1 Actor ac1 {
2   service msg1() {
3     ac1.msg2();
4     ac2.msg3();
5   }
6   service msg2() {
7     ac1.msg1();
8     ac2.msg4();
9   }
10 }
11 Actor ac2 {
12   int sv = 1;
13   service msg3() {
14     ac1.msg1();
15   }
16   service msg4() {
17     if (sv == 1)
18       sv = 4;
19     else
20       sv = 3;
21   }
22 }
23
24 main {
25   ac1.msg1();
26 }
    
```

Figure 1: An example of a simple actor model.

- $Vars$ is the set of variable names, and
- $Mtds$ is the set of method declarations.

Here, the members of $Mtds$ are tuples $(m, p, s) \in MName \times Vars^* \times Statement^*$, where m is the name of the message which must be served by this method, p is the lists of message parameters, and $s \in Statement^*$ is the sequence of statements comprising the method's body.

The set of statements in SAM is limited to a number of preliminary statements defined below.

Definition 2 (SAM Statements) The set of SAM statements is defined as $Statement = Assignment \cup Condition \cup Send$ where:

- $Assignment = Vars \times Expr$ is the set of assignment statements. In Figure 1, we use $var = expr$ to denote the assignment statement $(var, expr)$.
- $Condition = BExpr \times Statement^* \times Statement^*$ is the set of conditional statements. In Figure 1, we use $if(bexpr) \sigma \text{ else } \sigma'$ to denote the conditional statement $(bexpr, \sigma, \sigma')$.
- $Send = (ID \cup \{self\}) \times MName \times Expr^*$ is the set of send statements. In Figure 1, we use $a.m(e)$ to denote the send statement (a, m, e) .

In the aforementioned items, $Expr$ denotes the set of integer expressions defined using usual arithmetic operators (with no side effects). $BExpr$ denotes the set of Boolean expressions defined using usual relational and logical operators. We dispense with further details of the syntax in this definition.

Based on Definition 1 and Definition 2, a SAM model is specified by $\mathcal{P}(Actor) \cup Send^*$ where the $Send^*$ term addresses the send statements of the `main` block (i.e. the initially sent messages). Note that since there may be more than one initial message for an actor, the send statements are ordered in a sequence not just a set of statements.

We define below the operational semantics of SAM in terms of a Labeled Transition System (LTS). In order to do this, the following assumptions and notations are required. We assume that the only possible communication mechanism among actors is asynchronous message passing. The type of messages is defined as $Msgs = ID \times MName \times ID \times (Vars \rightarrow Vals)$, where for a message $(a_1, m, a_2, arg) \in Msgs$, a_1 is the name of the sending actor, a_2 is the name of the receiving actor, m is the name of the message, and arg is a function for mapping argument names to their values. For the sake of simplicity and without loss of generality, we assume that the messages do not have arguments and are left out of the message signature in the remainder of this paper. The other assumption is that the received messages of an actor are stored in a FIFO mailbox. Hence, the mailbox of an actor is denoted by a sequence of messages, i.e., a member of $Msgs^*$.

Definition 3 (SAM Operational Semantics) For a given actor model AC , its labeled transition system $LTS(AC)$, is defined as a tuple $(S, s_0, Act, \rightarrow)$, where:

- S is the set of the global states of a SAM model defined as a set of functions in form of $S = \{s \mid s : ID \rightarrow (Vars \rightarrow Vals) \times Msgs^*\}$. Here, $s \in S$ maps an actors identifier to the local state of the actor, i.e., the values of its state variables and its mailbox content,

- $s_0 \in S$ is the initial state,
- $Act = Msgs$ is the set of action labels (sent messages).
- $\rightarrow \subseteq S \times Act \times S$ is the set of transitions, defined by the coarse-grained interleaving of actor message executions, by removing a message from their mailboxes, sending the messages in the body of the corresponding method and finally updating the global state (as the result of assignment statements). By coarse-grained interleaving, we mean that the sequence of messages in the body of a method are sent in an atomic sequence.

Using the operational semantics of actor models, Clinger’s event diagram of actor models can be created. Clinger’s event diagram comprise vertices (called *dots*) for each event, and edges (called *arrows*) that represent the activation relation of two events. Using dots and arrows, the runtime characteristics of an actor system is presented by the graph of activation relation of events. Clinger’s event diagram is typically drawn using parallel vertical swim-lanes for actors, where the dots are placed respecting their sequential execution order. Figure 2(a) presents the Clingers’ event diagram of the example actor model of Figure 1. As shown in the actor model, message msg_1 is the first executing message (as it is put in the queue of ac_1 in the *main* block) which results in sending msg_2 and msg_3 ; hence, there is one *dot* with label msg_1 , which is connected by *arrows* to two other *dots* with labels msg_2 and msg_3 .

Clinger’s event diagrams can be seen as detailed representations of CDG. Intuitively, a CDG represents the possible activation relations of events derived from a static analysis of the model. Hence, a CDG over-approximates the event activations in the Clinger’s event diagram. The activation relation of events in a CDG can be extracted from the source codes of actor models. For example, as shown in Figure 2(a), the static activation relation between msg_1 and two messages msg_2 and msg_3 can be extracted from the source code of Figure 1. In addition, the execution of msg_3 results in the activation of msg_1 , hence, the loop back to the topmost state of the CDG in Figure 2(b).

Definition 4 (Sent Messages) For a given message $msg = (a_1, m, a_2) \in Msgs$, the set of messages that can be possibly sent by a_2 to arbitrary actors as a result of serving m (which is in turn sent by a_1) is denoted by $snt(msg)$.

The set $snt(msg)$ is statically determined by an evaluation of an actor model. For a given message $msg = (a_1, m, a_2)$ assume that (m, p, s) is its corresponding method. The members of $snt(msg)$ is computed by the analysis of the statements of the actor s , as depicted below for a given SAM model $sam = actors \cup snt_msgs$.

$$snt(msg) = \{msg' \in Msgs \mid \begin{aligned} &msg = (a_1, m, a_2) \wedge msg' = (a_2, m', a_i) \wedge (a_2, vars, mtds) \in actors \rightarrow \\ &\exists stmts \in \mathcal{P}(Statements) \cdot (m, arg, stmts) \in mtds \wedge (a_i, m', \emptyset) \in stmts \end{aligned} \}$$

Definition 5 (Call Dependency Graph (CDG)) Given an actor model AC with $LTS(AC) = (S, s_0, Act, \rightarrow)$, its CDG is a finite labeled transition system $CDG(AC) = (V, v_0, Act, \leftrightarrow)$, where

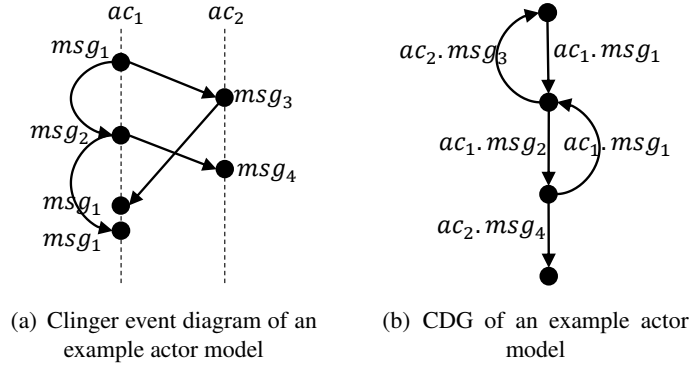


Figure 2: Clinger event diagram versus CDG of an example actor model.

$V \subseteq Act \times \mathcal{P}(Act)$ is the set of vertices (states), $v_0 \in V$ is the initial vertex (state), and $\hookrightarrow \subseteq V \times Act \times V$ is the set of edges (transitions). For two given states $u, v \in V$, there is $(u, act, v) \in \hookrightarrow$ if and only if $u = (act, pm)$ and $\exists (a_i, m', a_j) \in pm$ such that $v = ((a_i, m', a_j), snt(a_i, m', a_j))$. This way, the initial state of a CDG is defined as $v_0 = (\varepsilon, pm)$ where $(\varepsilon, m, a_i) \in pm$ and there is a send statement in form of $a_i.m()$ in the `main` block of AC. \square

This way, as the definition of the CDG is based on the sent messages and the sent messages are computed by static analysis of an actor model, the CDG can be created when the target actors of sent messages can be found by static analysis. So, only the actor models which do not support dynamic creation and dynamic binding of actors are in the scope of this work.

Next, we show that the abstract notion of the CDG reflects the cycles of the state space; more precisely, our goal is to show that each cycle in the LTS of an actor model can be projected into at least one cycle in the corresponding CDG.

Definition 6 (Labels, Sub-Traces, Sub-Cycles, and Cycles) Given an actor model AC a finite trace tr of $LTS(AC) = (S, s_0, Act, \rightarrow)$ is any finite word $m_i, m_{i+1}, \dots, m_n \in M^*$ such that there is a sequence $s_i, s_{i+1}, \dots, s_n, s_{n+1}$ of vertices in $LTS(AC)$, where for any two consequent states s_j and s_{j+1} there is $(s_j, m_j, s_{j+1}) \in \rightarrow$.

The set of cycles of $LTS(AC)$, denoted by $Cycles(LTS(AC))$, is the set of all traces that start and end with the same message. A sub-trace of a cycle which starts and ends with the same message is called a sub-cycle. The set of all edge labels of a given trace tr is denoted by $Labels(tr)$. \square

Using the aforementioned definition, the projection is reduced to proving that each cycle in $LTS(AC)$ as the state space of the actor model AC, has a sub-cycle in $CDG(AC)$. In order to prove this property, we first prove the following lemma, which establishes a link between individual messages appearing in the cycles of the state space and those appearing in the CDG. Here *appear* means that the message is the label of at least one of the transitions of the state space.

Lemma 1 For each message m appearing in $LTS(AC)$ of actor model AC, m also appears in $CDG(AC)$.

Proof. Assume that there exist messages which appear in the state space but never appear in the CDG. Pick one such message m that is reachable with the shortest trace from the initial state. Assume that m is sent in the body of a service m' . Due to the minimality assumption for m , m' should appear in the CDG and by the definition of CDG, m should appear in the CDG subsequent to the edge labeled m' (i.e., m' is the parent of m), contradicting our original assumption. \square

We also need the following definition.

Definition 7 (Parent and ancestors) Assume that $LTS(AC)$ and a trace $m_k \rightarrow \dots \rightarrow m_t \rightarrow m_j \rightarrow m_i \in tr(LTS(AC))$ are given, m_j is called the *parent* of m_i , and is denoted by $P(m_i)$. In addition, all messages from m_k to m_t are called the *ancestors* of m_i . \square

Theorem 1 (Mapping $LTS(AC)$ Cycles into CDG Cycles) *Each cycle in $LTS(AC)$ as the state space of the actor model AC , has a sub-cycle in $CDG(AC)$.*

Proof. Consider a cycle $c_{LTS} \in Cycles(LTS(AC))$ and an arbitrary label $m \in Label(c_{LTS})$; we claim that for each trace $m \rightarrow \dots \rightarrow m'$ in the traces of c_{LTS} , there exists a sub-trace $m \rightarrow \dots \rightarrow m'$ in $CDG(AC)$. Once we prove this claim, the theorem follows by taking $m \rightarrow \dots \rightarrow m = c_{LTS}$ as the antecedent of the claim (then, it follows from the claim that there should exist a sub-cycle of c_{LTS} in the CDG, which was to be shown).

To prove the claim, we use induction on the length of the trace $m \rightarrow \dots \rightarrow m'$. The base case follows from Lemma 1. Assume that the claim holds for all traces of length n or less and consider a trace $m \rightarrow \dots \rightarrow m'$ of length $n + 1$. Let M be the set of parents of m' in all cycles of CDG (by Lemma 1, m' should appear in at least one cycle of the CDG). There exists some $m_i \in M$ such that $m \rightarrow \dots \rightarrow m' = m \rightarrow \dots \rightarrow m_i \rightarrow \dots \rightarrow m'$. The trace $m \rightarrow \dots \rightarrow m_i$ is of length n (or less) and hence the induction hypothesis applies and a sub-trace of it appears in $CDG(AC)$. Since m_i is a parent of m' in the $CDG(AC)$, an edge labeled m' follows after m_i . Therefore $m \rightarrow \dots \rightarrow m_i \rightarrow m'$ is a trace of CDG , which was to be shown. \square

3 Using CDG in Distributed LTL Model Checking Algorithms

In this section, we show how CDG can be exploited to improve the efficiency of state distribution policy in distributed LTL model checking algorithms. As mentioned before, decreasing the number of split transitions reduces the required communication and hence the distributed model checking cost. Here, we show that how using CDG of actor models results in a better distribution of states in the distributed model checking of actor models. In the following, we show that how the CDG-based policy is implemented for distributed BFS-based LTL model checking algorithm.

3.1 BFS-based LTL Model Checking algorithm

The BFS-based exploration algorithm, creates and explores the state space in a level-by-level fashion and examines the back edges of the state space graph for cycle detection (explained below). In the first step of the BFS algorithm, the Cartesian product of the initial state of the state space and the property (i.e., the Büchi automaton which corresponds to the given property)

is stored, is marked as visited, and its level is set to zero. Then, for each level the successors of the states of that level are generated by applying the successor function to both the state space and the property automaton and their level is set by increasing the current level by one; when there are no unexplored states in the next level, the algorithm terminates.

This algorithm can be implemented using two queues to manage states of each level. The first queue stores the current level states (CLQ) and the second one stores the successors of the CLQ states. The latter queue is called the next level queue (NLQ). In each iteration, the unexplored states of the CLQ are dequeued and their unvisited successors are generated. When all states of the CLQ are dequeued, the content of the NLQ is moved to the CLQ and the algorithm continues until the NLQ is empty, i.e., all successors of the states in the CLQ have been visited. There is no need to examine all visited states, because only *back edges* may create cycles. Figure 1 shows a pseudo code of this algorithm with explores the state space and creates the Cartesian product of a given state space and a property automaton. The backward search algorithm done by function ACCEPTING-CYCLE-DETECTION(\cdot) the same as the algorithm given in [BC06].

Algorithm 1: BFS-MODEL-CHECKING($systemInitState, propertyInitState$) traverses a given state space level by level and detects the existing accepting cycles.

Input: The initial state $initState$
Output: The result of the model checking

```

1  $CLQ \leftarrow \{ \langle systemInitState, propertyInitState \rangle \}$ 
2  $NLQ \leftarrow \emptyset$ 
3  $Visited \leftarrow \emptyset$ 
4 while  $CLQ \neq \emptyset$  do
5   foreach state  $\langle s, p \rangle \in CLQ$  do
6     foreach system state  $s' \in \text{SUCCESSORS}(s)$  do
7       foreach property state  $p' \in \text{P-SUCCESSORS}(p, s')$  do
8         if  $\langle s', p' \rangle \notin Visited$  then
9            $Visited \leftarrow Visited \cup \{ \langle s', p' \rangle \}$ 
10           $NLQ \leftarrow NLQ \cup \{ \langle s', p' \rangle \}$ 
11         else
12           ACCEPTING-CYCLE-DETECTION( $\langle s', p' \rangle$ )
13    $CLQ \leftarrow NLQ$ 
14    $NLQ \leftarrow \emptyset$ 

```

In the following, function SUCCESSORS(\cdot) computes the successor states of its given system state and P-SUCCESSORS(\cdot) computes the property successor states based on its given property state and system state.

3.2 Distributed BFS Model Checking Algorithm

A major difference between the centralized- and the distributed BFS model checking (BFS-MC) algorithm is in storing the next level states. In the centralized BFS-MC, all newly generated

system states are stored in the NLQ but in the distributed BFS-MC, some of them should be sent to other nodes of the cluster. In other words, each state has a host node. The host of a state is the node that is responsible for storing the state and generating its successors.

Algorithm 2: DISTRIBUTED-BFS-MODEL-CHECKING($initState, id$) traverses a given state space level by level.

Input: The initial state $\langle systemInitState, propertyInitState \rangle$ (which is *null* if this node is not the host of the initial state) and the node's id

Output: The result of the model checking

```

1  $CLQ \leftarrow \langle systemInitState, propertyInitState \rangle$ 
2  $NLQ \leftarrow \emptyset$ 
3  $Visited \leftarrow \emptyset$ 
4  $allFinished \leftarrow false$ 
5 while  $\neg allFinished$  do
6   foreach  $state \langle s, p \rangle \in CLQ$  do
7     foreach  $system\ state\ s' \in SUCCESSORS(s)$  do
8        $hostId \leftarrow HASH-VALUE(s')$ 
9       foreach  $property\ state\ p' \in P-SUCCESSORS(p, s')$  do
10        if  $id = hostId$  then
11          if  $\langle s', p' \rangle \notin Visited$  then
12             $Visited \leftarrow Visited \cup \langle s', p' \rangle$ 
13             $NLQ \leftarrow NLQ \cup \langle s', p' \rangle$ 
14          else
15            ACCEPTING-CYCLE-DETECTION( $\langle s', p' \rangle$ )
16          else
17            SEND( $\langle s', p' \rangle, hostId$ )
18   SYNCHRONIZE-ALL()
19    $CLQ \leftarrow NLQ$ 
20    $NLQ \leftarrow \emptyset$ 
21    $allFinished \leftarrow ALL-HOSTS-CLQ-IS-EMPTY()$ 

```

Line 8 of Algorithm 2 shows host assignment based on the random distribution. After finding the host, if the newly generated state host is the same as its parent's and it has not yet been visited, then the state is stored in NLQ. In contrast, if the newly generated state's host is another node, the state is sent to it. Then, the host node receives the new state and checks if the state is visited before. To this aim, the receiving algorithm, i.e. Algorithm 3, is run in parallel with the Algorithm 2 in each node. Therefore, checking whether a state is visited or not can be done locally.

The other difference between the centralized and the distributed BFS-MC is in the cluster nodes synchronization phase at the end of each iteration (line 21). In the synchronization phase, nodes that finish processing their CLQ wait for other nodes to finish their work. Hence, after

Algorithm 3: RECEIVER($NLQ, allFinished$) receives the sent states.

Input: Reference to the next level queue NLQ and the termination flag $allFinished$

```

1 while  $\neg allFinished$  do
2    $\langle s, p \rangle \leftarrow$  RECEIVE-FROM-NETWORK()
3   if  $\langle s, p \rangle \notin Visited$  then
4      $Visited \leftarrow Visited \cup \{\langle s', p' \rangle\}$ 
5      $NLQ \leftarrow NLQ \cup \{\langle s', p' \rangle\}$ 

```

synchronization, all nodes have processed their CLQ states and are ready to continue the search for the next level. If none of the nodes have any new state to explore, the value of `allFinished` is set to `true` in line 24 to terminate the model checking.

3.3 States Distribution Policy based on CDG

In the new state distribution policy, we find the set of active cycles for each state. The active cycles of each state are found in the CDG of the model and are based on the messages which can be executed in that state. Without loss of generality, we base the definition of our distribution policy on the simple cycles in a CDG (i.e., cycles with no repetition of vertices). When exploring the transitions of a state, we store the states that belong to a cycle of the CDG on the same cluster node, (i.e., states with the same active cycles).

Definition 8 (Active cycles of a state) Consider an actor model A and its CDG $CDG(A) = (V, v_0, Act, \rightarrow)$. For a given state $v \in V$, the set of active cycles of v is the subset of $Cycles(CDG(A))$ containing all cycles in which the label m_j appear, where m_j is a label of one of the outgoing edges of state v .

The implementation of the new distribution policy is given in Algorithm 4. As shown in the input section, the CDG of the model is generated before model checking and it is given as an input to the algorithm. The main difference between Algorithms 2 and the new algorithm is in the way of finding hosts in Algorithm 4. Namely, line 8 of Algorithm 2 is replaced with the CDG-based distribution policy of lines 8 to 11.

4 Experimental Results

We implemented CDG-based distribution policy for the BFS-based distributed model checking engine of Rebeca, an actor-based language with a Java-like syntax ¹. We studied the impacts of using CDG in the state space generation and the analysis against reachability properties, using the current implementation of the Rebeca distributed model checking toolset. The test platform has been Ubuntu 9.10 on a cluster of 2.2GHz Pentium 4 Core2 Duo with 2GB of RAM storage

¹ A brief description about Rebeca and how the CDG of a Rebeca model is obtained is described in the full version of this paper in the Rebeca homepage

Algorithm 4: DISTRIBUTED-BFS-MODEL-CHECKING($initState, id, CDG$) traverses a given state space level by level.

Input: The initial state $initState$ (which is *null* if this node is not the host of the initial state), the node's id , and CDG as the call dependency graph of the model

Output: The result of the model checking

```

1  $CLQ \leftarrow \{ \langle systemInitState, propertyInitState \rangle \}$ 
2  $NLQ \leftarrow \emptyset$ 
3  $Visited \leftarrow \emptyset$ 
4  $allFinished \leftarrow false$ 
5 while  $\neg allFinished$  do
6   foreach  $state \langle s, p \rangle \in CLQ$  do
7     foreach  $system\ state\ s' \in SUCCESSORS(s)$  do
8        $activeCycles \leftarrow \emptyset$ 
9       foreach  $message\ msg \in ENABLED-MESSAGE(s')$  do
10         $activeCycles \leftarrow activeCycles \cup CDG-CYCLES(CDG, msg)$ 
11       $hostId \leftarrow CHOOSE-CYCLE(activeCycles)$ 
12      foreach  $property\ state\ p' \in P-SUCCESSORS(p, s')$  do
13        if  $id = hostId$  then
14          if  $\langle s', p' \rangle \notin Visited$  then
15             $Visited \leftarrow Visited \cup \{ \langle s', p' \rangle \}$ 
16             $NLQ \leftarrow NLQ \cup \{ \langle s', p' \rangle \}$ 
17          else
18             $ACCEPTING-CYCLE-DETECTION(\langle s', p' \rangle)$ 
19          else
20             $SEND(\langle s', p' \rangle, hostId)$ 
21   $SYNCHRONIZE-ALL()$ 
22   $CLQ \leftarrow NLQ$ 
23   $NLQ \leftarrow \emptyset$ 
24   $allFinished \leftarrow ALL-HOSTS-CLQ-IS-EMPTY()$ 

```

for each cluster node. We chose the size of each cluster based on the number of simple cycles in the CDG of each case study.

Three different case studies are used to compare the execution time and the memory consumption among centralized model checking, distributed model checking with random distribution policy, and distributed model checking with distribution policy based on CDG. The examples are the asynchronous resource manager, dining philosophers, and train controller models.

In the dining philosophers model, there are a number of philosophers sitting at a round table. Between each adjacent pair of philosophers, there is a chopstick. To model such a behavior, each philosopher can be in one of the following states: thinking, hungry, or eating. A philosopher thinks for a while, and then stops thinking and becomes hungry. When the philosopher becomes hungry, she cannot eat until he owns both of the chopsticks to her left and right. When the philosopher is done eating she puts down the chopsticks and begins thinking again.

In the train controller model there are a number of trains on each side of the bridge. Trains arrive non-deterministically and the controller has to manage them in such a way that only one train passes the bridge at a time, because there is one railway on the bridge. Each train announces its arrival to the controller and the controller lets the train enter the bridge, if there is no other train on the bridge. If the bridge is full then the arrived train is put in a queue. The waiting trains will be served respectively. Each train should faithfully declare its departure to the controller. The Rebeca code of each case study can be found at the Rebeca homepage [fml].

Each example represents different pattern of communication and synchronization: the dining philosophers example shows a ring topology, the train controller and the asynchronous resource manager show a star topology. In the dining philosophers example, each actor sends requests and responses to its left and right neighbors. In the train controller, the bridge controller behaves like a binary semaphore, whereas in the resource manager, the central node behaves like a counting semaphore.

The asynchronous resource manager is model checked for deadlock freedom with 4 to 7 clients (5 to 8 rebecs). The dining philosophers example is model checked for deadlock freedom with 2 to 5 philosophers (4 to 10 rebecs). The train controller model is model checked for deadlock freedom with 2 to 8 trains (3 to 9 rebecs). Tables 1 and 2 show the results.

In the CDG-based distribution policy in comparison to the random distribution, there is the overhead of cycle membership check and instead we have fewer split transitions and less communication among cluster nodes for cycle detection. Our results show that time-wise the gain exceeds the overhead.

As shown in Table 1 in the large enough cases, the number of split edges in the CDG-based distribution policy is 50% to 70% of the random distribution policy. In addition, memory consumption is reduced, because storing the split transitions requires storing endpoints host ids of the edges. This improvement is about 10% for the asynchronous resource manager and 5% for the train controller.

Table 2 shows the gain in the execution time that is about 8% for the asynchronous resource manager and 13% for the train controller in their largest versions. For the dining philosophers model, although the split cycles for the CDG-based policy are 52% of the random-based policy, the execution time remains the same. This is due to the many back edges and the big cycles in the state space. In this case the CDG-based policy reduces the split edges but the effect of the reduction is negligible comparing to the time spent for backward search in detecting accepting

Problem	Size	#Transitions	#Split Transitions		
			Random	CDG	improvement
Asynch. Resource Manager	2 clients	94	39	36	8%
	3 clients	818	540	432	20%
	4 clients	7,76K	5,83K	4516	23%
	5 clients	83,19K	66,52K	50,46K	25%
	6 clients	1,02M	850,74K	635,14K	26%
	7 clients	14,34M	12,30M	9,01M	27%
Dining Philosophers	2 phils	408	196	107	46%
	3 phils	10,30K	6,97K	4,81K	31%
	4 phils	206,00K	154,76K	75,86K	51%
	5 phils	3,78M	3,02M	1,60M	47%
Train Controller	2 trains	86	46	36	22%
	3 trains	620	433	296	32%
	4 trains	4,46K	3,35	2,29K	32%
	5 trains	33,30K	26,66K	18,17K	32%
	6 trains	265,89K	221,61K	148,32K	34%
	7 trains	2,30M	1,97M	1,30M	35%
	8 trains	21,83M	19,11M	12,40M	36%

Table 1: Split edges in the random and the CDG-based distribution policies.

cycles.

We also measured load balancing of cluster nodes for the two distributed policies. Random distribution results in balanced load for each node. In our experimental results, we could see that in random distribution, the deviation from the best distribution starts from 9% in small models and reduces to less than 1% for the larger one. In the CDG distribution this deviation starts from 13% and reduces to 1.28% for larger models.

In general the experimental results show that our technique outperforms random distribution when the size of the model is large enough. The gain increases as the size of the model grows. Also in our approach, the load balancing of cluster nodes converges to the optimum point in larger examples.

5 Discussion, Conclusion and Future Work

In this paper we introduced the Call Dependency Graph (CDG) for the actor-based modeling languages. The CDG is generated by a static analysis of the model and is an abstract graph capturing the causality of message passing among actors. We designated and proved a relation between the cycles in the CDG and the cycles in the state space. We devised a distribution policy for the distributed model checker of *Rebeca* based on the CDG. The new distribution policy increases the efficiency of distributed model checking by increasing the locality of the accepting cycles. Our new policy is implemented as an extension of breadth first search distributed model checking. Experimental evidence supports that this new policy improves cycle locality, and decreases model checking time and memory in practice.

As future work, we plan to improve our algorithm by duplicating states to avoid split cycle creation such that all cycles can be detected locally. This comes at the cost of more memory consumption, and we need to define a set of criteria to balance between the increase in the size of state space, due to duplicating states, and the decrease in the verification time, due to localizing

Problem	Size	#States	Time (sec)		
			Centralized	Random	CDG
Asynch. Resource Manager	2 clients	51	0	0	0
	3 clients	344	0	1	1
	4 clients	2,86K	0	4	4
	5 clients	28,78K	1	6	6
	6 clients	344,24K	157	24	21
	7 clients	4,71M	> 6 hour	1846	1704
Dining Philosophers	2 phils	183	0	1	1
	3 phils	3,06K	2	8	8
	4 phils	46,01K	381	209	209
	5 phils	675,56K	> 6 hour	4821	4818
Train Controller	2 trains	46	0	0	0
	3 trains	250	0	1	1
	4 trains	1,51K	0	2	2
	5 trains	10,19K	1	3	3
	6 trains	76,64K	9	4	4
	7 trains	641,74K	1147	26	24
	8 trains	5,96M	> 6 hour	3192	2789

Table 2: Time consumption for centralized and distributed model checking with the random and the CDG-based distribution policies.

cycles. Moreover, we look for property classes for which our distribution policy guarantees localized cycles. Finally, we would like to investigate the effect of incorporating CDG into other analysis and reduction techniques such as slicing.

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