

**“Security Protocol Verification and Optimization by Epistemic Model Checking”**

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**Abstract:**

When a distributed systems protocol is used in a particular context as part of a solution to a larger problem, additional information may be generated from the context. Such information may be used for optimization of the system, and, in the case of security protocols, may be of use to the adversary for attacks. The project conducted a case study of the application of the epistemic model checker MCK to automatically detect such optimization opportunities, and to verify that the protocol remains secure in the mode of use.

The particular protocol studied was Chaum’s Dining Cryptographers protocol, a security protocol that allows a single agent to anonymously transmit a signal. The context of use considered was a more general 2-phase protocol for anonymous broadcast by an arbitrary number of agents, also proposed by Chaum. The aims of the 2-phase anonymous broadcast protocol were formulated as a knowledge-based program, and an iterative process of model checking and manual counter-example guided refinement was followed to converge on implementations of this knowledge-based program in which local predicates were identified that correspond precisely to the knowledge conditions in the knowledge-based program. This analysis demonstrated that the 2-phase protocol contains some quite subtle flows of information that can be used to optimize its performance, but no violation of the anonymity property was found.

As an additional contribution of the research, a formal abstraction technique was developed, and proved correct, for epistemic model checking of protocols that call the Dining Cryptographers protocol as a subroutine. Experimental results show that the optimization improves epistemic model checking performance by orders of magnitude and enables problems of larger scale to be attacked.

**Introduction:**

Distributed systems protocols are typically used as building blocks in the development of systems whose primary goals are application specific and not known to the protocol designers. Verification of protocols, on the other hand, has generally been studied from the point of view of the protocol running in isolation. When a protocol is composed with another, or applied in a particular context, additional information becomes available both to the trusted agents and their adversaries.

The adversaries may be able to use this additional information in their attacks, breaking the security of the protocol. This issue is related to what is known in the literature on information flow security as the “refinement paradox”: composition and specialization reduces the nondeterminism of a system, and security properties such as secrecy and anonymity are not preserved under reduction of nondeterminism. On the other hand, the additional information also has a positive side: the trusted agents may be able to exploit this additional information to optimize the execution of the protocol. The scientific problem that this raises is how such opportunities for attacks and optimization may be detected and utilized.

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14. ABSTRACT

**When a distributed systems protocol is used in a particular context as part of a solution to a larger problem, additional information may be generated from the context. Such information may be used for optimization of the system, and, in the case of security protocols, may be of use to the adversary for attacks. The project conducted a case study of the application of the epistemic model checker MCK to automatically detect such optimization opportunities, and to verify that the protocol remains secure in the mode of use. The particular protocol studied was Chaum's Dining Cryptographers protocol, a security protocol that allows a single agent to anonymously transmit a signal. The context of use considered was a more general 2-phase protocol for anonymous broadcast by an arbitrary number of agents, also proposed by Chaum. The aims of the 2-phase anonymous broadcast protocol were formulated as a knowledge-based program, and an iterative process of model checking and manual counter-example guided refinement was followed to converge on implementations of this knowledge-based program in which local predicates were identified that correspond precisely to the knowledge conditions in the knowledge-based program. This analysis demonstrated that the 2-phase protocol contains some quite subtle flows of information that can be used to optimize its performance, but no violation of the anonymity property was found. As an additional contribution of the research, a formal abstraction technique was developed, and proved correct, for epistemic model checking of protocols that call the Dining Cryptographers protocol as a subroutine. Experimental results show that the optimization improves epistemic model checking performance by orders of magnitude and enables problems of larger scale to be attacked.**

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The project conducted a case study of the use of epistemic model checking, in particular the model checker MCK<sup>1</sup>, as a tool for the automated support of the analysis of such issues in protocol composition.

Model checking, a tool-supported verification methodology, involves the development of a formal model of key aspects of a system to be verified, and an automated check that this model satisfies specifications written in a formal logic. Model checking is usually conducted for specifications in temporal logic, expressing how the system behaves over time. *Epistemic model checking* extends this capability to include specifications that talk about knowledge. It allows properties such as “Whenever the acknowledgement is received, the agent *knows* that the original message was delivered” to be expressed. MCK is a model checker developed at UNSW that handles such richer specifications. It is unique amongst model checkers of this type in dealing with the “perfect recall” semantics for knowledge, which interprets an agent’s knowledge to be everything that it can infer from all its observations to the present moment of time. (Other epistemic model checkers generally treat knowledge as what can be deduced from just the current observation.) The perfect recall interpretation is computationally expensive, but it is the appropriate one for analysis of systems from the point of view of maximizing use of potential information flow (either by adversaries or trusted agents).

In the following, we briefly summarise the work performed and results obtained, and refer to the papers cited for further details.

### **Approach:**

We studied a 2-phase protocol for anonymous broadcast proposed by Chaum<sup>2</sup>, that uses as a subroutine the simpler Chaum's Dining Cryptographers Protocol (henceforth the “DC protocol”). The DC protocol enables a single agent to anonymously broadcast a signal, assuming that it is common knowledge that at most one agent has a signal to send. The 2-phase protocol is intended for an arbitrary and possibly unknown number of agents to transmit a message. The 2-phase protocol is composed from multiple rounds of the DC protocol, in two phases: in the first phase, several rounds of the DC protocol are used to allow the agents wishing to broadcast to anonymously declare that they will transmit their information in a given slot. If no contention for a slot is detected in this phase then the information is sent in the selected slot by further application of the DC protocol. However, there may be contention for a slot that is not detected in the first phase – in this case there is a clash in the second phase.

Paper [1] gives a description of the methodology we followed to conduct an epistemic analysis of the 2-phase protocol. As a first step, we formulated the requirements for the 2-phase protocol as a knowledge-based program. Knowledge-based programs resemble ordinary programs except that their conditions may be stated in terms of formulas of the logic of knowledge expressing what an agent knows or does not know about its environment. Such programs cannot be directly executed, but can be said to be implemented by a standard program of a similar structure in which the knowledge conditions are replaced by concrete predicates of the local state of the agent. For the implementation relationship to hold, the concrete predicates must be equivalent to the knowledge condition that they replace. Our methodology involves the use of epistemic model checking to verify this equivalence in order to determine whether a putative implementation is in fact an implementation. When this check fails, the model checker returns a counter example that may be inspected in order to understand the reason for the failure. This information may then be used in order to revise the putative implementation. We then iterate this process until we find an actual implementation of the knowledge-based program. (The methodology is partially automated: verification and counter-example construction is done automatically by the model checker, analysis of the counter-example and revision of the putative implementation of the knowledge-based program is done by hand.)

In paper [1] we applied this methodology to an instance of the 2-phase protocol in which three agents

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<sup>1</sup> <http://www.cse.unsw.edu.au/~mck>

<sup>2</sup> D. Chaum. The dining cryptographers problem: Unconditional sender and recipient untraceability. *Journal of Cryptology*, pages 65-75, 1988.

contend for three transmission slots.

In [1], we already obtained some interesting conclusions about the protocol but the experiments demonstrated that we were working at the limits of the capability of the model checker, with some quite long runtimes. In the next phase of the study, we therefore developed an abstraction technique for the models, with the aim of optimizing model checking performance. Details of the optimization are given in paper [2], which develops a formal framework for the model checking optimization, states and proves related correctness theorems, and conducts experiments on its effectiveness. The analysis of the 2-phase protocol is also carried further in this paper, in particular, through the consideration of larger numbers of agents. (The maximum number of agents we considered was 5.)

## **Results and Discussion:**

At the most general level, the project was successful in providing a demonstration, by means of the case study conducted, of the feasibility and usefulness of the epistemic model checking methodology for the analysis of protocols in distributed systems. Since epistemic model checking is a comparatively new technology, and only a few nontrivial case studies of its application have been conducted to date, this is a valuable contribution to the literature.

More specifically, as a result of our analysis we have discovered a number of subtle flows of information in the 2-phase protocol. (The details are given in section 11 of [2].) Notably, these discoveries were made not through a pencil and paper analysis, but by studying the counterexamples that were automatically generated by the model checker. Furthermore, for all the types of knowledge we considered, we were able to *completely characterize* (in instances of up to 5 agents) the situations under which an agent has that knowledge, as well as to automatically verify that characterization.

For example, it turns out that the circumstances under which an agent knows that it has received a bit of value 1 from some other agent are significantly more complicated than the condition identified by Chaum: viz., that the value 1 appears in the second round in some slot that has been successfully booked in the first round, but in which the agent is not itself transmitting. In fact, the agent also knows that another has transmitted the value 1 when it transmits in some slot on which there has been a collision that was not detected in the first round, and it observes that the result of its transmission is the opposite of what it transmitted. Our model checking experiments confirm that these two situations completely characterize the situations under which an agent knows that another has transmitted the bit 1.

As another example, the characterization of the circumstances under which an agent knows that its message has been successfully transmitted turns out to be even more complex: it requires counting the number of slots reserved in the first phase of the protocol and observing the outcomes of transmissions on slots other than the ones on which the agent is transmitting. Our model checking approach was valuable both in discovering this characterization (see Section 11 of [2] for details) and in verifying its correctness.

Characterizations such as these of knowledge conditions relevant to the goals of the protocol help to obtain optimized implementations of the protocol. For example, the characterization of the conditions under which an agent knows that its message has been successfully transmitted helps to optimize the protocol by allowing the agent to stop its transmission attempts at the earliest possible time.

As well as the above use of the methodology for protocol optimization, we also verified using epistemic model checking that the anonymity goal of the protocol holds in the variants studied. No violations of the anonymity property were found in our experiments.

In addition to these contributions relating to the case study, we have also made contributions to the model checking methodology itself. In order to obtain reasonable runtimes in our experiments, we found it was necessary to develop an abstraction technique that provides a formal justification for a simplification of the models being checked: the simpler models yield the same model checking results, but with significantly faster runtimes. One of our contributions in this project is a formal

statement and proof of a theorem stating that the abstraction is correct. Furthermore, we have conducted experiments that demonstrate the effectiveness of the abstraction technique: we obtained runtime improvements as large as two to three orders of magnitude, enabling problems with larger numbers of agents to be model checked with reasonable runtimes than was possible without the optimization. (The number of agents we considered is still modest, but we note that the instances, measured using the number of variables in the symbolic representation scales quadratically with the number of agents, and the model checking problem is NP-complete in the size of the symbolic representation.) Section 10 of paper [2] describes these experimental results.

### **Conclusions for future research:**

In addition to the work described above, our original research plan proposed, in the best case, work on a number of variants of the 2-phase protocol, including study of faulty or malicious agents in this context, as well as related protocols proposed by Andreas Pfitzman. We conducted some preliminary work in this direction that we were not able to complete, as one project risk envisaged, the potentially limited mathematical experience of the student working on the project, did in practice turn out to significantly impact the rate of progress on the most demanding part of the project, the correctness proof for the abstraction result.

Another of the obstacles encountered in this work was the long runtimes for model checking on larger scale instances of such protocol variants. Even when applying our abstraction, model checking is only possible for instances with a modest number of agents. Furthermore, the particular abstraction we developed in this project does not apply to attacks at the level of the original Dining Cryptographers protocol, e.g., in which agents falsely make broadcasts that are not compliant with the protocol, in an attempt to gain advantage.

However, we believe that further (and more general) optimizations can be developed for the epistemic model checking problems of the kind we have studied. A number of studies of epistemic model checking of protocols with respect to the perfect recall semantics have applied model checkers for the observational rather than perfect recall semantics of knowledge. For this, models have been constructed, by hand, in such a way that a single observation contains the same information as the agent's history of observations in a perfect recall model. When this is possible, the experimental results show that problems of large scale (e.g. with as many as 50 agents) can be model checked for epistemic properties in reasonable time, since model checking with respect to the observational semantics is significantly more efficient than with respect to the perfect recall semantics. On the other hand, the way that this optimization has been obtained in the past is entirely ad-hoc, performed by hand, and it has not been justified in a formal way. There is therefore a significant risk that the observational models constructed miss flows of information that are available in the perfect recall model.

It would be desirable to have a more systematic understanding of optimizations of this kind for problems of the type we have studied. In temporal logic model checking, an apparently related optimization has been used, the technique of program slicing, which is used to reduce a model/program to the fragment that is actually relevant for the specific formula to be model checked. This can be formally justified, can be automated, and results in significant optimizations of model checking performance. To date, no similar techniques have been studied for epistemic model checking. We believe the development of slicing-like techniques for epistemic model checking would have the potential to result in significant improvements in both the performance and trustworthiness of epistemic model checking analyses of the kind we studied in this project. We hope to pursue this idea in future work.

**List of Publications:**

[1] [Epistemic Model Checking for Knowledge-Based Program Implementation: an Application to Anonymous Broadcast](#), O. Al-Bataineh and R. van der Meyden, SecureComm'10, 6th International ICST Conference on Security and Privacy in Communication Networks, Singapore, Sept 7-9 2010. An earlier version of this paper also appears on CORR as <http://arxiv.org/abs/1010.2287>.

[2] [Abstraction for Epistemic Model Checking of Dining Cryptographers-based Protocols](#), Omar I. Al-Bataineh and R. van der Meyden, Oct 2010. (A full version of this paper appears on CORR as <http://arxiv.org/abs/1010.2287>, and an extended abstract has been submitted to a conference for publication.)

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# Abstraction for Epistemic Model Checking of Dining Cryptographers-based Protocols <sup>\*</sup>

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**Abstract.** The paper describes an abstraction for protocols that are based on multiple rounds of Chaum's Dining Cryptographers protocol. It is proved that the abstraction preserves a rich class of specifications in the logic of knowledge, including specifications describing what an agent knows about other agents' knowledge. This result can be used to optimize model checking of Dining Cryptographers-based protocols, and applied within a methodology for knowledge-based program implementation and verification. Some case studies of such an application are given, for a protocol that uses the Dining Cryptographers protocol as a primitive in an anonymous broadcast system. Performance results are given for model checking knowledge-based specifications in the concrete and abstract models of this protocol, and some new conclusions about the protocol are derived.

## 1 Introduction

Relations of abstraction (and their converse, refinement) are valuable tools for program verification. In this approach, we relate a (structurally complex) concrete program to a (simpler) abstract program by means of a relation that is known to preserve the properties that we wish to verify in the concrete program. When such a relation can be shown to hold, we are able to verify these properties in the concrete program by showing that they hold in the abstract program, which is generally easier in view of the lesser structural complexity of the abstract program. In particular, model checkers can be expected to run more efficiently on the abstract program than on the concrete program, and abstraction is often used to bring the verification problem within the bounds of feasibility for model checking. Conversely, starting with the abstract program, and having verified that this satisfies the desired properties, we may derive the concrete program

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and conclude that this also satisfies these properties. This perspective is the basis for “correctness-by-construction” or top-down refinement approaches to program verification.

Our contribution in this paper is to establish the correctness of an abstraction relation for abstract programs based on use a trusted third party for anonymous broadcast, which is implemented in the related concrete programs by means of the *Dining Cryptographers* protocol proposed by Chaum [4]. That Chaum’s protocol implements anonymous broadcast is, of course, well-known, but we show that this statement holds in a more general sense than is usually considered in the literature, where the focus is generally on the very particular property of anonymity. Specifically, we consider a broad class of properties formulated in the logic of knowledge, including properties in which agent knowledge is nested, such as “Alice knows that Bob knows that  $p$ ”. We show that the abstraction relation between programs based on the trusted third party and programs based on the Dining Cryptographers protocol preserves all properties from this class.

As an application of this result, we consider a protocol from Chaum’s paper [4] that uses multiple rounds of the Dining Cryptographers protocol to build a more general anonymous broadcast system. We have previously studied this protocol from the perspective of a model checking based methodology for the implementation of knowledge-based programs [2], by treating the specification of the protocol as a knowledge-based program containing nested knowledge formulas.

Knowledge-based programs [9] are an abstract, program-like form of specification, that describe how an agent’s actions are related to conditions stated in terms of the agent’s knowledge. The advantage of this level of abstraction is that it provides a highly intuitive description of the intentions of the programmer, that has been argued to be easier to verify than the complex implementations one typically finds for highly optimized distributed programs [14, 9]. Knowledge-based programs cannot be directly implemented, however, so they must be *implemented* by concrete programs in which the knowledge conditions are replaced by concrete predicates of the agent’s local state. The implementation relation between a knowledge-based program and a putative implementation holds when these concrete predicates are equivalent to the knowledge formulas that they replace (interpreted with respect to the system generated by running the putative implementation). Our partially-automated methodology for the implementation of knowledge-based programs uses a model checker for the logic of knowledge to check whether this equivalence holds, and if it does not, uses the counter-examples generated by the model checker to generate a revised putative implementation. (This process is iterated until an implementation is found.)

In our previous work on the application of this methodology, we considered model checking problems generated in this way from a knowledge-based program based on multiple rounds of the Dining Cryptographers protocol. Our experience was that the model checking problems we considered were close to the bounds of feasibility for our model checker even for instances with small numbers of agents, and we were prevented from considering instances of scale

as a result. In the present paper, we apply our abstraction result in order to optimize the model checking problem, by performing model checking on the abstracted (trusted third party) version of the programs we consider rather than the concrete (Dining Cryptographers based) versions. We give performance results showing the difference, which indicate that the abstraction is effective in reducing the model checking runtime by several orders of magnitude, enabling systems involving larger numbers of rounds of the Dining Cryptographers protocol and larger numbers of agents to be model checked. We use the efficiency gains to extend our previous analysis of the knowledge based program to larger numbers of agents, leading to an improved understanding of its implementations.

The structure of the paper is as follows. We begin in Section 2 by introducing the logic of knowledge, which provides the specification language for the properties that are preserved by our abstraction technique, and give its semantics in terms of a class of Kripke structures. We define a notion of bisimulation on these Kripke structures that provides the semantic basis for our program abstraction technique. In Section 3, we introduce a simple programming language used to represent our concrete and abstract programs. In Section 4, we introduce the Dining Cryptographers protocol and, in Section 5, its abstraction using a trusted third party. In Section 6 we state and prove correct the abstraction relation. The remainder of the paper deals with our application of this result. We recall the two-phase protocol in Section 7. In Section 8 we describe knowledge-based programs and an approach to the use of model checking to identify their implementations. In Section 9 we recall our formulation of the two-phase protocol as a knowledge-based program and describe the associated verification conditions. Section 10 discusses the comparative performance of model checking in the concrete and abstract models when using the model checker MCK. We highlight some of the interesting conclusions we are able to make about implementations of the knowledge-based program for the round-based protocol in Section 11. We discuss related work in Section 12. Finally, in Section 13, we draw some conclusions and discuss future directions.

## 2 Epistemic Logic and Bisimulations

Epistemic logics are a class of modal logics that include operators whose meaning concerns the information available to agents in a distributed or multi-agent system. In epistemic model checking, one is generally concerned with the combination of such operators with temporal operators, and a semantics using a class of structures known in the literature as *interpreted systems* [9] that combines temporal and epistemic expressiveness. We focus here on a simpler framework that omits temporal operators, since we are mostly interested, in our application, on what knowledge agents have after some program has run, and this also simplifies the statement and proof of our results.

Suppose that we are interested in systems comprised of agents from a set  $Agt$  whose states are described using a set  $Var$  of boolean variables.<sup>1</sup> The syntax of the logic of knowledge  $\mathcal{L}_{(Var, Agt)}$  is given by the following grammar:

$$\phi ::= \top \mid v \mid \neg\phi \mid \phi \wedge \phi \mid K_i\phi$$

where  $v \in Var$  is a variable and  $i \in Agt$  is an agent. (We freely use standard boolean operators that can be defined using the two given.) Intuitively, the meaning of  $K_i\phi$  is that agent  $i$  knows that  $\phi$  is true.

The semantics for the language is given in terms of *Kripke structures* of the form  $M = (Agt, W, \{\sim_i\}_{i \in Agt}, Var, \pi)$ , where

1.  $Agt$  is the set of agents,
2.  $W$  is a set of worlds, or situations,
3. for each  $i \in Agt$ ,  $\sim_i$  is an equivalence relation on  $W$ ,
4.  $Var$  is a set of variables,
5.  $\pi : W \times Var \rightarrow \{0, 1\}$  is a valuation.

Intuitively,  $W$  is the set of situations that the agents consider that they could be in, and  $w \sim_i w'$  if, when the actual situation is  $w$ , agent  $i$  considers it possible that they are in situation  $w'$ . The value  $\pi(w, v)$  is the truth value of variable  $v$  in situation  $w$ . Such a Kripke structure  $M$  is *fit* for the language  $\mathcal{L}_{(Var', Agt')}$  if  $Agt' \subseteq Agt$  and  $Var' \subseteq Var$ . The semantics of the language is given by the relation  $M, w \models \phi$ , where  $M$  is a Kripke structure fit for  $\mathcal{L}_{(Var, Agt)}$ ,  $w$  is a world of  $M$ , and  $\phi$  is a formula, meaning intuitively that the formula  $\phi$  holds at the world  $w$ . The definition is given inductively by

1.  $M, w \models v$  if  $\pi(w, v) = 1$ , for  $v \in Var$ .
2.  $M, w \models \neg\phi$  if not  $M, w \models \phi$ ,
3.  $M, w \models \phi_1 \wedge \phi_2$  if  $M, w \models \phi_1$  and  $M, w \models \phi_2$ ,
4.  $M, w \models K_i\phi$  if  $M, w' \models \phi$  for all  $w' \in W$  with  $w \sim_i w'$ , for  $i \in Agt$ .

Intuitively, the final clause says that agent  $i$  knows  $\phi$  if it does not consider it possible that not  $\phi$ . We write  $M \models \phi$ , and say that  $\phi$  is *valid* in  $M$ , if  $M, w \models \phi$  for all  $w \in W$ . The *Kripke structure model checking* problem is to compute, given  $M$  and  $\phi$ , whether  $M \models \phi$ . We will use this formulation of the model checking problem as the basis for another notion of model checking, to be introduced below, that concerns a way of generating  $M$  from a program.

One of the difficulties to be faced in model checking, the *state space explosion* problem, is the potentially large size of the set of worlds  $W$  of the structures  $M$  of interest. Abstractions are useful techniques for mitigating state space explosion problem. They are often applied as a preliminary step to model checking. Systems often encode details that are irrelevant to the properties that we aim to verify. Abstraction techniques enable us to eliminate such unnecessary, redundant details. However, abstractions must be sound, in the sense that properties that hold in the abstract model must also hold in the concrete model.

<sup>1</sup> We use the term “variable” rather than “proposition” in this paper, since our atomic propositions arise as boolean variables in a program.

For Kripke structures, *bisimulations* may provide an effective way to simplify redundant structure while preserving properties of interest. We formulate here a version that is suited to our application, in which we allow both the set of agents and the set of propositions to vary in the structures we consider.

Suppose we are given a set of variables  $Var$ , a set of agents  $Agt$ , and two Kripke structures

$$M = (Agt^M, W^M, \{\sim_i^M\}_{i \in Agt^M}, Var^M, \pi^M)$$

and

$$N = (Agt^N, W^N, \{\sim_i^N\}_{i \in Agt^N}, Var^N, \pi^N)$$

such that  $Agt \subseteq Agt_M \cap Agt_N$  and  $Var \subseteq Var^M \cap Var^N$ . (Note that these conditions imply that both  $M$  and  $N$  are fit for  $\mathcal{L}_{(Var, Agt)}$ .) A  $(Var, Agt)$ -bisimulation  $\mathfrak{R}$  between  $M$  and  $N$  is defined to be a binary relation  $\mathfrak{R} \subseteq W^M \times W^N$  such that:

1. **Atoms:**  $\pi^M(w, v) = \pi^N(w', v)$  whenever  $w \mathfrak{R} w'$  and  $v \in Var$ ;
2. **Forth:** if  $i \in Agt$ , and  $w_1, w_2$  are two worlds in  $M$  and  $u_1$  is a world in  $N$  such that  $w_1 \sim_i^M w_2$  and  $w_1 \mathfrak{R} u_1$ , then there is a world  $u_2 \in W^N$  such that  $u_1 \sim_i^N u_2$  and  $w_2 \mathfrak{R} u_2$ ; and
3. **Back:** if  $i \in Agt$  and  $u_1, u_2$  are two worlds in  $N$  and  $w_1$  is a world in  $M$  such that  $u_1 \sim_i^N u_2$  and  $u_1 \mathfrak{R} w_1$ , then there is a  $w_2 \in W^M$  such that  $w_1 \sim_i^M w_2$  and  $u_2 \mathfrak{R} w_2$ .

If there exists an  $(Var, Agt)$ -bisimulation  $\mathfrak{R}$  between  $M$  and  $N$  such that  $w \mathfrak{R} u$ , then we write  $(M, w) \approx_{(Var, Agt)} (N, u)$ . If there exists an  $(Var, Agt)$ -bisimulation  $\mathfrak{R}$  between  $M$  and  $N$  such that for every  $u \in W^M$  there exists  $w \in W^N$  such that  $u \mathfrak{R} w$  and, conversely, for every  $w \in W^N$  there exists  $u \in W^M$  such that  $u \mathfrak{R} w$ , then we write  $M \approx_{(Var, Agt)} N$ . The following result shows that  $(Var, Agt)$ -bisimulation preserves properties in the language  $\mathcal{L}_{(Var, Agt)}$ .

**Lemma 1.** *If  $M$  and  $N$  are Kripke structures and  $u$  and  $w$  are worlds of  $M$  and  $N$  such that  $(M, u) \approx_{(Var, Agt)} (N, w)$ , then for all  $\varphi \in \mathcal{L}_{(Var, Agt)}$  we have  $M, u \models \varphi$  if and only if  $N, w \models \varphi$ . If  $M \approx_{(Var, Agt)} N$  then for all  $\varphi \in \mathcal{L}_{(Var, Agt)}$  we have  $M \models \varphi$  if and only if  $N \models \varphi$ .*

We omit the proof since it is a minor variant of well-known results in the literature. In our applications of this result, we will consider a complex, concrete structure  $M$  and a simpler, more abstract structure  $N$ , and show that  $M \approx_{(Var, Agt)} N$ . This enables us to verify  $M \models \varphi$  using the model checking problem  $N \models \varphi$ , which is likely to be computationally easier in view of the smaller size of  $N$ . However, we need to also develop an abstraction technique for the programs that generate these Kripke structures. We develop this technique in the following sections.

### 3 A Programming Language and its Semantics

We use a small multi-agent programming language equipped with a notion of observability. All variables are Boolean, and expressions are formed from variables using the usual Boolean operators. The language has the following atomic actions, in which  $i$  and  $j$  are agents,  $x$  is a variable name and  $e$  is an expression:

1.  $i : x := e$  — agent  $i$  evaluates  $e$  and assigns the result to  $x$ ,
2.  $i : rand(x)$  — agent  $i$  assigns a random value to  $x$ ,
3.  $i : e \rightarrow j.x$  — agent  $i$  evaluates  $e$  and transmits the result across a private channel to agent  $j$ , who assigns it to its variable  $x$ ,
4.  $i : broadcast(x)$  — agent  $i$  broadcasts the value of the variable  $x$  to all other agents.

Note that we write  $i.x$  for agent  $i$ 's variable  $x$  (the variables  $i.x$  and  $j.x$  are considered distinct when  $i \neq j$ ) but may omit the agent name when this is clear from the context. In particular, in an atomic action  $i : a$ , any variable  $x$  not explicitly associated with an agent refers to  $i.x$ . For example, we may write  $i : x := y \otimes z$  rather than  $i : i.x := i.y \otimes i.z$ . Similarly, when  $e$  is an expression in which agent indices are omitted, and  $i$  is an agent, the expression  $i.e$  refers to the result of replacing each occurrence of a variable name  $x$  in  $e$  that is not already associated to an agent index with  $i.x$ . Thus  $i.(y \otimes j.z)$  represents  $i.y \otimes j.z$ .

Each atomic action *reads* and *writes* certain variables. Specifically, the action  $i : x := e$  reads the (agent  $i$ ) variables in  $e$  and writes  $i.x$ , the action  $i : rand(x)$  reads nothing and writes  $i.x$ , the action  $i : e \rightarrow j.x$  reads the (agent  $i$ ) variables in  $e$  and writes  $j.x$ , and the action  $i : broadcast(x)$  reads  $x$  and writes nothing. A *joint action* is a set of atomic actions in which no variable is written more than once. Intuitively, a joint action is executed by first evaluating all the expressions and then performing a simultaneous assignment to the variables.

A *program* is given by a sequence of joint actions  $A_1; \dots; A_n$ . A *program for agent  $i$*  is a program in which each atomic action  $j : a$  in any step has  $j = i$ . We permit parallelism within an agent, in the sense that we do *not* require that a joint action contains at most one atomic action for each agent. If we are given for each agent  $i$  a program  $P_i = A_1^i; \dots; A_n^i$ , all of the same length  $n$ , then we may form the joint program  $\parallel_i P_i = (\cup_i A_1^i); \dots; (\cup_i A_n^i)$ .

Some well-formedness conditions are required on agent programs. An *observability mapping* is a function  $ov$  mapping each agent to a set of variables, intuitively, the set of variables that it may observe. A program runs in the context of an observability mapping, and modifies that mapping. We say that a *joint action  $A$  is enabled* at an observability map  $ov$  if

1. no variable written to by  $A$  is in  $ov(i)$  for any agent  $i$  (that is, all variables written to are *new* variables), and
2. for each atomic action  $i : x := e$  and  $i : e \rightarrow j.x$  in  $A$ , the expression  $i.e$  contains only variables in  $ov(i)$ , and
3. for each action  $i.broadcast(x)$  we have  $i.x \in ov(i)$ .

These constraints may be understood as access control constraints stating that agent  $i$  may read only the variables in  $ov(i)$  and may write only new variables.

Executing the action  $A$  transforms the observability map  $ov$  to the observability map  $ov[A]$  such that  $ov[A](i)$  is the result of adding to  $ov(i)$

1. all variables  $i.x$  such that an action of the form  $i : x := e$  or  $i : rand(x)$  or  $j : e \rightarrow i.x$  occurs in  $A$ , and
2. all variables  $j.x$  such that  $j : broadcast(x)$  occurs in  $A$ .

These definitions are generalised to programs: *the program  $P = A_1; \dots; A_n$  is enabled* at the observability map  $ov$  if for each  $i = 1 \dots n$ , the action  $A_i$  is enabled at  $ov[A_1] \dots [A_{i-1}]$ , and we define  $ov[P]$  to be  $ov[A_1] \dots [A_n]$ .

*Example 1.* Consider a two-agent system with agents  $i, j$ . The action  $\{i : x := j.y\}$  is not enabled at the observability map  $ov$  given by  $\{j \mapsto \{j.y\}\}$ . However, the program  $\{j : broadcast(y)\}; \{i : x := j.y\}$  is enabled at  $ov$ , since the action  $\{j : broadcast(y)\}$  is enabled at  $ov$ , and transforms  $ov$  to  $ov[\{j : broadcast(y)\}] = \{j \mapsto \{j.y\}, i \mapsto \{j.y\}\}$ , at which the action  $\{i : x := j.y\}$  is enabled.

We say that an observability map is *consistent* with a Kripke structure  $M = (Agt, W, \{\sim_i\}_{i \in Agt}, Var, \pi)$  when for all agents  $i$ , if  $v$  is a variable in  $ov(i)$  then  $v \in Var$ , and for all worlds  $w, w' \in W$  such that  $w \sim_i w'$  we have  $\pi(w, v) = \pi(w', v)$ . Intuitively,  $ov$  is consistent with  $M$  if all variables declared to be local to agent  $i$  by  $ov$  are in fact defined and semantically local to agent  $i$  in  $M$ .

The *program  $P$  is enabled at a Kripke structure  $M$*  if there exists an observability map  $ov$  such that

1.  $ov$  is consistent with  $M$ ,
2.  $P$  is enabled at  $ov$ , and
3. all variables  $x$  written by  $P$  are not defined in  $M$  (i.e.,  $x \notin Var$ ).

In particular, note that if a single joint action  $A$  is enabled at  $M$ , then for all variables  $x$  read by  $A$ , and all worlds  $w$ , the value  $\pi(w, x)$  is defined. Consequently, we may also evaluate at  $w$  any expression  $e$  required to be computed by  $A$ . We write  $\pi(w, e)$  for the result.

We can now give a semantics of programs, in which a program applied to a Kripke structure representing the initial states of information of the agents, transforms the structure into another Kripke structure representing the states of information of the agents after running the program. The definition is given inductively, on an action-by-action basis. Let  $M = (Agt, W, \{\sim_i\}_{i \in Agt}, Var, \pi)$  be a Kripke structure and  $A$  a joint action. We define a Kripke structure  $M[A] = (Agt', W', \{\sim'_i\}_{i \in Agt'}, Var', \pi')$  as follows. Let  $V$  be the set of variables  $i.x$  such that  $A$  includes the atomic action  $i : rand(x)$ . Intuitively, such actions increase the amount of non-determinism in the system, whereas all other actions have deterministic effects. We define  $Agt' = Agt$  and take  $W'$  to be the set of states of the form  $(w, \kappa)$  where  $w \in W$  and  $\kappa : V \rightarrow \{0, 1\}$  is an assignment of boolean values to the variables in  $V$ . We may write  $w + \kappa$  for the pair  $(w, \kappa)$ . In case  $V$  is the empty set,  $\kappa$  is always the null function, so we may write just  $w$  for

$(w, \kappa)$ . The set  $Var'$  of variables defined in  $M[A]$  is obtained by adding to  $Var$  all variables written to by  $A$ . The assignment  $\pi'$  is obtained by extending  $\pi$  to these new variables by defining  $\pi'$  as follows on worlds  $w + \kappa$ :

1. if  $v \in Var$  then  $\pi'(w + \kappa, v) = \pi(w, v)$ ,
2. if  $i : x := e$  occurs in  $A$  then  $\pi'(w + \kappa, i.x) = \pi(w, i.e)$ ,
3. if  $i : rand(x)$  occurs in  $A$  then  $\pi'(w + \kappa, i.x) = \kappa(i.x)$ , and
4. if  $j : e \rightarrow i.x$  occurs in  $A$  then  $\pi'(w + \kappa, i.x) = \pi(w, j.e)$ .

Finally, the indistinguishability relations  $\sim'_i$  are defined using the observability map  $ov[A]$ : we define  $w + \kappa \sim'_i w' + \kappa'$  when  $w \sim_i w'$  and for all variables  $x$  in  $ov[A](i) \setminus ov(i)$ , we have  $\pi'(w + \kappa, x) = \pi'(w' + \kappa', x)$ . Intuitively, this reflects that the agent recalls any information it had in the structure  $M$ , and adds to this information that it is able to observe in the new state. Note that in fact  $w + \kappa \sim'_i w' + \kappa'$  implies  $\pi'(w + \kappa, x) = \pi'(w' + \kappa', x)$  for *all* variables  $x \in ov[A](i)$ , since we have assumed that for  $x \in ov(i)$  we have that  $w \sim_i w'$  implies  $\pi(w, x) = \pi(w', x)$ . Moreover, since the set  $ov[A](i) \setminus ov(i)$  is just the set of variables written to by  $A$  that are made observable to  $i$ , this observation also yields that the definition of  $M[A]$  is independent of the choice of observation map  $ov$  consistent with  $M$ .

## 4 Chaum's Dining Cryptographers Protocol

Chaum's Dining Cryptographers protocol is an example of an anonymous broadcast protocol: it allows an agent to send a message without revealing its identity. Chaum introduces the protocol with the following story:

Three cryptographers are sitting down to dinner at their favourite restaurant. Their waiter informs them that arrangements have been made with the maitre d'hotel for the bill to be paid anonymously. One of the cryptographers might be paying for the dinner, or it might have been NSA (U.S National Security Agency). The three cryptographers respect each other's right to make an anonymous payment, but they wonder if NSA is paying. They resolve their uncertainty fairly by carrying out the following protocol:

Each cryptographer flips an unbiased coin behind his menu, between him and the cryptographer on his right, so that only the two of them can see the outcome. Each cryptographer then states aloud whether the two coins he can see—the one he flipped and the one his left-hand neighbor flipped—fell on the same side or on different sides. If one of the cryptographers is the payer, he states the opposite of what he sees. An odd number of differences uttered at the table indicates that a cryptographer is paying; an even number indicates that NSA is paying (assuming that the dinner was paid for only once). Yet if a cryptographer is paying, neither of the other two learns anything from the utterances about which cryptographer it is.

Chaum shows that this protocol solves the problem, and notes that it can be considered as a mechanism enabling a signal to be anonymously transmitted, under the assumption that at most one of the agents wishes to transmit. He goes on to generalize the idea to  $n$ -agent settings where, in place of the ring of coins, we have a graph representing the key-sharing arrangement.

The more general protocol can be represented in our programming language as follows. We assume that there is a set  $Agt$  of agents, who share secrets based on a (directed) key sharing graph  $G = (Agt, E)$  in which the vertices are the agents in  $Agt$  and the edges  $E \subseteq Agt \times Agt$  describe the keysharing arrangement amongst the agents. We model keysharing by assuming that for each edge  $e = (i, j)$ , agent  $i$  generates the key corresponding to the edge, and communicates the key to  $j$  across a secure channel. For each edge  $e = (i, j)$  we write  $e_1$  for the source agent  $i$  and  $e_2$  for the destination agent  $j$ . For each agent  $i$  we define  $in(i) = \{e \in E \mid e_2 = i\}$  and  $out(i) = \{e \in E \mid e_1 = i\}$ . Accordingly, we use two variables for each edge  $e = (i, j)$ : the variable  $i.k_e$  stores  $i$ 's copy of the key corresponding to the edge, and the variable  $j.k_e$  stores  $j$ 's copy. We write  $keys(i)$  for  $in(i) \cup out(i)$ , i.e., the set of edges incident on  $i$ . The protocol  $DC_i(m)$  of an agent  $i \in Agt$  (in which the message represented by the expression  $i.m$  is transmitted anonymously by agent  $i$ ) consists of the following five steps:

$$\begin{aligned}
 DC_i(m) = & \{i : rand(k_e) \mid e \in out(i)\}; \\
 & \{i : k_e \rightarrow e_2.k_e \mid e \in out(i)\} \\
 & \{i : b := m \otimes \otimes_{e \in keys(i)} k_e\}; \\
 & \{i : broadcast(b)\}; \\
 & \{i : rr := \otimes_{j \in Agt} j.b\}
 \end{aligned}$$

**Figure 1: The protocol  $DC$**

We write  $DC(m)$  for the joint program  $\parallel_{i \in Agt} DC_i(m)$ .

Intuitively, the protocol  $DC$  operates by first generating keys and setting up the key sharing graph, and then having each of the agents make a public announcement encrypted using all the keys available to them. The directionality of an edge in the key sharing graph indicates who generates the key corresponding to the edge, viz, the source agent of the edge. The first step of the protocol corresponds to each agent generating the key values for which they are responsible. In the second step, these keys are shared with the other agent on the edge by transmission across a secure channel. Each agent now has the value of each of the key edges on which it is incident, and computes the xor of its message with all these key values in the 3rd step, and broadcasts the result in the 4th step. In the final step of the protocol, each agent computes the xor of the messages broadcast as the result of the protocol.



## 5 An Abstraction of the Dining Cryptographers Protocol

We are interested in protocols in which the DC protocol is used as a basic building block, and in model checking the agent's knowledge in the resulting protocols. In order to optimize this model checking problem, we now introduce a protocol that we will show to be an abstraction of the DC protocol that preserves epistemic properties.

The abstracted version of the protocol omits the use of keys, but adds to the set of agents a trusted third party  $T$  who computes the result of the protocol on behalf of the agents, and then broadcasts it. Here, we take  $Agt^a = Agt \cup \{T\}$ . The protocol  $DC_i^a(m)$  for agent  $i$  is given in four steps, see Figure 2. We

$DC_i^a(m) = \{i : m \rightarrow T.x_i\}; \text{ (for } i \in Agt)$ $\{\};$ $\{\};$ $\{i : rr := y\}$	$DC_T^a(m) = \{\};$ $\{T : y := \otimes_{i \in Agt} x_i\};$ $\{T : broadcast(y)\};$ $\{\}$
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**Figure 2: The abstract protocol  $DC^a$**

write  $DC^a(m)$  for the joint program  $\parallel_{i \in Agt^a} DC_i^a(m)$ . Intuitively, in the abstract protocol, the agents transmit their bits across a secure channel to the trusted third party, who computes the exclusive-or and broadcasts it.

Note that since the protocol  $DC^a$  makes no use of randomization, the set of worlds of the structure  $M[DC^a(m)]$  is identical to the set of worlds of the structure  $M$ ; only the set of defined variables and the indistinguishability relation change. We can characterize the indistinguishability relations of  $M[DC^a(m)]$  as follows, where we introduce the abbreviation  $\otimes m$  for  $\otimes_{i \in Agt} i.m$ .

**Lemma 2.** *If  $M$  is a Kripke structure at which  $DC^a(m)$  is enabled, and  $u, v$  are worlds of  $M[DC^a(m)]$  then  $u \sim_i^{M[DC^a(m)]} v$  iff  $u \sim_i^M v$  and  $\pi^M(u, \otimes m) = \pi^M(v, \otimes m)$ .*

The program  $DC(m)$  makes use of randomization, so the structure  $M[DC(m)]$  has more worlds than the structure  $M$ . More specifically, it can be seen that the worlds of  $M[DC(m)]$  have the form  $((w, \kappa_1), \kappa_2)$ , where  $\kappa_1$  assigns boolean values to the variables  $i.k_e$  for  $e \in E$  and  $i = e_1$ , and  $\kappa_2$  assigns boolean values to the variables  $i.k_e$  for  $e \in E$  and  $i = e_2$ . Note that by the second step of the protocol, we always have  $\kappa_1(e_1.k_e) = \kappa_2(e_2.k_e)$  for all  $e \in E$ . We may therefore abbreviate such a world to  $w + \kappa$ , where  $\kappa : E \rightarrow \{0, 1\}$ , and we have

1.  $\pi^{M[DC(m)]}(w + \kappa, e_1.k_e) = \kappa(e)$ ,
2.  $\pi^{M[DC(m)]}(w + \kappa, e_2.k_e) = \kappa(e)$ ,
3.  $\pi^{M[DC(m)]}(w + \kappa, i.b) = \pi(w, i.m) \otimes \otimes_{e \in keys(i)} \kappa(e)$ , and
4.  $\pi^{M[DC(m)]}(w + \kappa, i.rr) = \otimes_{j \in Agt} \pi^{M[DC(m)]}(w + \kappa, j.b)$ .

Note that the final equation may be simplified as follows:

$$\begin{aligned}
\pi^{M[DC(m)]}(w + \kappa, i.r.r) &= \otimes_{j \in \text{Agt}} \pi^{M[DC(m)]}(w + \kappa, j.b) \\
&= \otimes_{j \in \text{Agt}} (\pi^{M[DC(m)]}(w + \kappa, j.m) \otimes \otimes_{e \in \text{keys}(j)} \kappa(e)) \\
&= (\otimes_{j \in \text{Agt}} \pi^M(w, j.m)) \\
&= \pi^M(w, \otimes m)
\end{aligned}$$

where the third step follows using the fact each term  $\kappa(e)$  occurs twice, once for  $e \in \text{keys}(e_1)$  and once for  $e \in \text{keys}(e_2)$ . Based on this representation, we can characterize the indistinguishability relations of  $M[DC(m)]$  as follows:

**Lemma 3.** *If  $M$  is a Kripke structure at which  $DC(m)$  is enabled, and  $u + \kappa$  and  $v + \lambda$  are worlds of  $M[DC(m)]$  then  $u + \kappa \sim_i^{M[DC(m)]} v + \lambda$  iff*

1.  $u \sim_i^M v$  and
2.  $\kappa(e) = \lambda(e)$  for all  $e \in \text{keys}(i)$  and
3.  $\pi^M(u, j.m) \otimes \otimes_{e \in \text{keys}(j)} \kappa(e) = \pi^M(v, j.m) \otimes \otimes_{e \in \text{keys}(j)} \lambda(e)$  for all  $j \in \text{Agt}$ .

## 6 Proof of Abstraction

The following is implicit<sup>2</sup> in the proof of a key result concerning the DC protocol that is proved in Chaum [4] (Section 1.4).

**Lemma 4.** *For all  $i \in \text{Agt}$  and for all functions  $\kappa : E \rightarrow \{0, 1\}$  and  $\mu : \text{Agt} \rightarrow \{0, 1\}$  and  $\mu' : \text{Agt} \rightarrow \{0, 1\}$  such that  $\otimes_{i \in \text{Agt}} \mu(i) = \otimes_{i \in \text{Agt}} \mu'(i)$ , there exists a function  $\lambda : E \rightarrow \{0, 1\}$  such that  $\kappa \upharpoonright \text{keys}(i) = \lambda \upharpoonright \text{keys}(i)$  and for all  $j \in \text{Agt}$ , we have  $\mu(j) \otimes \otimes_{e \in \text{keys}(j)} \kappa(e) = \mu'(j) \otimes \otimes_{e \in \text{keys}(j)} \lambda(e)$*

Note that the variables introduced by  $DC(m)$  are the variables  $i.k_e$ ,  $i.b$  and  $i.r.r$  for  $i \in \text{Agt}$  and  $e \in E$ . The variables introduced by  $DC^a(m)$  are  $T.x_i$ ,  $T.y$  and  $i.r.r$  for  $i \in \text{Agt}$ . Hence the set of variables introduced by both protocols is the set  $\{i.r.r \mid i \in \text{Agt}\}$ . The following result states that these variables are introduced by these protocols in such a way as to extend a bisimulation between given concrete and abstract structures to the new variables.

**Theorem 1.** *Suppose that  $M \approx_{V, \text{Agt}} M^a$  for a set of variables  $V$  containing all variables in the expressions  $i.m$  for  $i \in \text{Agt}$ , and let  $DC(m)$  be enabled at  $M$  and  $DC^a(m)$  be enabled at  $M^a$ . Then  $M[DC(m)] \approx_{V \cup \{i.r.r \mid i \in \text{Agt}\}, \text{Agt}} M^a[DC^a(m)]$ .*

*Proof.* Let  $M = \langle W, \text{Agt}, \{\sim_i\}_{i \in \text{Agt}}, \text{Prop}, \pi \rangle$  and let

$$M^a = \langle W^a, \text{Agt}^a, \{\sim_i^a\}_{i \in \text{Agt}^a}, \text{Prop}^a, \pi^a \rangle .$$

We write

$$M[DC(m)] = \langle W', \text{Agt}, \{\sim'_i\}_{i \in \text{Agt}}, \text{Prop}', \pi' \rangle$$

<sup>2</sup> Chaum's result is stated probabilistically, but the proof is largely non-probabilistic and establishes this result.

and

$$M^a[DC^a(m)] = \langle W^{a'}, Agt^a, \{\sim_i^{a'}\}_{i \in Agt^a}, Prop^{a'}, \pi^{a'} \rangle .$$

As noted above, we have  $W^{a'} = W^a$  and

$$W' = \{w + \kappa \mid w \in W, \kappa : E \rightarrow \{0, 1\}\} .$$

Let  $R \subseteq W \times W^a$  be the bisimulation relation witnessing  $M \approx_{V, Agt} M^a$ . We define the relation  $\mathfrak{R} \subseteq (W' \times W^{a'})$  as follows:  $w + \kappa \mathfrak{R} w'$  if  $wRw'$ . We claim that this relation witnesses  $M[DC(m)] \approx_{V \cup \{i.rr \mid i \in Agt\}, Agt} M^a[DC^a(m)]$ .

*Atoms:* We need to check that for all  $v \in V \cup \{i.rr \mid i \in Agt\}$ , if  $w + \kappa \mathfrak{R} w'$  then  $\pi'(w + \kappa, v) = \pi^{a'}(w', v)$ . For propositions  $v \in V$ , this is immediate from the facts that  $w + \kappa \mathfrak{R} w'$  implies  $wRw'$ , that  $R$  is a  $(V, Agt)$ -bisimulation, and that  $\pi'(w + \kappa, v) = \pi(w, v)$  and  $\pi^{a'}(w', v) = \pi^a(w', v)$ . For the variables  $i.rr$ , we argue as follows. Note that since the variables in  $i.m$  are included in  $V$ , it follows that  $\pi'(w + \kappa, i.m) = \pi^{a'}(w', i.m)$ , and hence that  $\pi'(w + \kappa, \otimes m) = \pi^{a'}(w', \otimes m)$ . As noted above, we have  $\pi'(w + \kappa, i.rr) = \pi'(w + \kappa, \otimes m)$ . By the program for  $DC^a(m)$ , we also have  $\pi^{a'}(w', i.rr) = \pi^{a'}(w', \otimes m)$ . Combining these equations yields  $\pi'(w + \kappa, i.rr) = \pi^{a'}(w', i.rr)$ . Thus, we have that  $\mathfrak{R}$  preserves all propositions in  $V \cup \{i.rr \mid i \in Agt\}$ .

*Forth:* Let  $i \in Agt$ ,  $u + \kappa, v + \lambda \in W'$ , and let  $u^{a'} \in W^{a'}$  such that  $u + \kappa \sim_i' v + \lambda$  and  $u + \kappa \mathfrak{R} u^{a'}$ . We need to show that there exists  $v^{a'} \in W^{a'}$  such that  $v + \lambda \mathfrak{R} v^{a'}$  and  $u^{a'} \sim_i^{a'} v^{a'}$ . We argue as follows. From  $u + \kappa \mathfrak{R} u^{a'}$  it follows that  $uRu^{a'}$ . Also, from  $u + \kappa \sim_i' v + \lambda$  it follows by Lemma 3 that  $u \sim_i v$ . Since  $R$  is a bisimulation, we obtain that there exists a world  $v^a \in W^a$  such that  $u^a \sim_i^a v^a$  and  $vRv^a$ . Since  $W^{a'} = W^a$  we may define  $v^{a'}$  to be  $v^a$ . It is immediate from the definition of  $\mathfrak{R}$  and the fact that  $vRv^{a'}$  that  $v + \lambda \mathfrak{R} v^{a'}$ . To show  $u^{a'} \sim_i^{a'} v^{a'}$  we use the characterization of  $\sim_i^{a'}$  of Lemma 2. We already have that  $u^{a'} \sim_i v^{a'}$  by construction, so it remains to show  $\pi^a(u^{a'}, \otimes m) = \pi^a(v^{a'}, \otimes m)$ .

From the fact that  $vRv^{a'}$ , and that all variables in  $i.m$  are in  $V$ , we have that  $\pi(v, \otimes m) = \pi^a(v^{a'}, \otimes m)$ . Similarly, from  $uRu^{a'}$ , we have that  $\pi(u, \otimes m) = \pi^a(u^{a'}, \otimes m)$ . Further, since  $u + \kappa \sim_i' v + \lambda$ , it follows by Lemma 3 that  $\pi(u, \otimes m) = \pi(v, \otimes m)$ . Combining these equations yields  $\pi^a(u^{a'}, \otimes m) = \pi^a(v^{a'}, \otimes m)$ , giving the remainder of what we require for the conclusion that  $u^{a'} \sim_i^{a'} v^{a'}$ .

*Back:* Let  $i \in Agt$ ,  $u + \kappa \in W'$ , and let  $u^{a'}, v^{a'} \in W^{a'}$  such that  $u + \kappa \mathfrak{R} u^{a'}$  and  $u^{a'} \sim_i^{a'} v^{a'}$ . We need to show that there exists  $v + \lambda \in W'$  such that  $u + \kappa \sim_i' v + \lambda$  and  $v + \lambda \mathfrak{R} v^{a'}$ . We identify the world  $v \in W$  as follows. From  $u + \kappa \mathfrak{R} u^{a'}$  we have that  $uRu^{a'}$  and from  $u^{a'} \sim_i^{a'} v^{a'}$  we have (by Lemma 3) that  $u^{a'} \sim_i^a v^{a'}$ . Since  $R$  is a bisimulation, there exists a value  $v \in W$  such that  $u \sim_i v$  and  $vRv^{a'}$ .

From  $u^{a'} \sim_i^{a'} v^{a'}$  and Lemma 2, we obtain that  $\pi^a(u^{a'}, \otimes m) = \pi^a(v^{a'}, \otimes m)$ , hence also  $\pi^a(u^{a'}, \otimes m) = \pi^a(v^{a'}, \otimes m)$ . From the fact that  $R$  is a bisimulation preserving the propositions  $V$ , we get from  $uRu^{a'}$  and  $vRv^{a'}$  that  $\pi(u, \otimes m) = \pi^a(u^{a'}, \otimes m)$  and  $\pi(v, \otimes m) = \pi^a(v^{a'}, \otimes m)$ . Combining these equations yields  $\pi(u, \otimes m) = \pi(v, \otimes m)$ .

Note that  $vRv^{a'}$  implies that  $v + \lambda \mathfrak{R} v^{a'}$  for all  $\lambda : E \rightarrow \{0, 1\}$ , giving half of what we require. It therefore remains to find a value of  $\lambda$  such that  $u + \kappa \sim'_i v + \lambda$ . Since we already have  $u \sim_i v$ , this requires, by Lemma 3, that we find  $\lambda$  such that  $\kappa(e) = \lambda(e)$  for all  $e \in \text{keys}(i)$  and  $\pi^M(u, j.m) \otimes_{e \in \text{keys}(j)} \kappa(e) = \pi^M(v, j.m) \otimes_{e \in \text{keys}(j)} \lambda(e)$  for all  $j \in \text{Agt}$ . Since  $\pi(u, \otimes m) = \pi(v, \otimes m)$ , the existence of such a function  $\lambda$  is guaranteed by Lemma 4, on taking  $\mu(i) = \pi(u, i.m)$  and  $\mu'(i) = \pi(v, i.m)$ .  $\square$

This result gives us that, modulo bisimulation, the programs  $DC(m)$  and  $DC^a(m)$  have the same effect on the agent's mutual states of knowledge. We have a similar result if we consider the effect of joint actions  $A$ :

**Lemma 5.** *Let  $M$  and  $M'$  be Kripke structures such that  $M \approx_{V, \text{Agt}} M'$ , and let  $A$  be a joint action, writing variables  $V_A$ , such that  $A$  is enabled at both  $M$  and  $M'$ . Then  $M[A] \approx_{V \cup V_A, \text{Agt}} M'[A]$ ,*

*Proof.* Suppose  $R$  is a bisimulation witnessing  $M \approx_{V, \text{Agt}} M'$ , and we represent the worlds of  $M[A]$  as  $w + \kappa$  where  $w$  is a world of  $M$  and  $\kappa : V_A \rightarrow \{0, 1\}$ , where  $\pi^{M[A]}(w + \kappa, v) = \kappa(v)$  for  $v \in V_A$ . (This requires some constraints on the set of  $w + \kappa$ , to handle the case of variables  $v \in V_A$  that are not written by  $i : \text{rand}(v)$  statements.) The worlds of  $M'[A]$  may be similarly represented as  $w + \kappa$  where  $w$  is a world of  $M'$ .

Then it is easily shown that the relation  $r'$  defined by  $u + \kappa R' v + \lambda$  if  $uRv$  and  $\kappa = \lambda$  is a bisimulation.  $\square$

Combining Theorem 1 and Lemma 5, we obtain the following by a straightforward induction. (Note that we use fresh variables  $k_e, b, rr, x_i$  and  $y$  in each of the instances of  $DC_i$  and  $DC_i^a$ .)

**Theorem 2.** *Let  $M$  and  $M^a$  be Kripke structures with  $M \approx_{V, \text{Agt}} M^a$ , and let*

$$P = Q_1; DC(m_1); Q_2; DC(m_2); \dots DC(m_k); Q_{k+1} \quad \text{and}$$

$$P^a = Q_1; DC^a(m_1); Q_2; DC^a(m_2); \dots DC^a(m_k); Q_{k+1}$$

*where the  $Q_i$  are programs involving agents  $\text{Agt}$ . Let  $V'$  be the set of all variables written by the programs  $Q_i$ , as well as the variables  $i.rr$  introduced by the  $DC$  instances. Assume that the  $Q_j$  and  $m_j$  read only variables from  $V \cup V'$ . Then if  $P$  is enabled at  $M$ , and  $P^a$  writes no variable in  $M^a$ , then  $P^a$  is enabled at  $M^a$  and  $M[P] \approx_{V \cup V', \text{Agt}} M^a[P^a]$ .*

This result states that if we have a complex protocol  $P$ , constructed by using multiple instances of the DC protocol interleaved with other actions, then we abstract  $P$  by abstracting each of the instances of  $DC$  to  $DC^a$ , while preserving the truth values of all epistemic formulas. This enables optimization of model checking epistemic formulas in  $M[P]$  by applying model checking to  $M[P^a]$  instead. (Note that always  $M \approx M$ .)

## 7 The Two-phase Anonymous Broadcast Protocol

As noted above, the basic version of the Dining Cryptographers protocol enables a signal to be anonymously transmitted under the assumption that at most one agent wishes to transmit. One of Chaum’s considerations is the use of the protocol for more general anonymous broadcast applications, and he writes:

The cryptographers become intrigued with the ability to make messages public untraceably. They devise a way to do this at the table for a statement of arbitrary length: the basic protocol is repeated over and over; when one cryptographer wishes to make a message public, he merely begins inverting his statements in those rounds corresponding to 1’s in a binary coded version of his message. If he notices that his message would collide with some other message, he may for example wait for a number of rounds chosen at random from some suitable distribution before trying to transmit again.

As a particular realization of this idea, he discusses grouping communication into blocks and the use of the following *two-phase broadcast* protocol using *slot-reservation*:

In a network with many messages per block, a first block may be used by various anonymous senders to request a “slot reservation” in a second block. A simple scheme would be for each anonymous sender to invert one randomly selected bit in the first block for each slot they wish to reserve in the second block. After the result of the first block becomes known, the participant who caused the  $i$ th bit in the first block sends in the  $i$ th slot of the second block.

This idea has been implemented as part of the Herbivore system[11].

Chaum’s discussion leaves open a number of questions concerning the protocol. For example, what exact test is applied to determine whether there is a collision? Which agents are able to detect a collision? Are there situations where some agent expects to receive a message, but a collision occurs that it does not detect (although some other agent may do so?) Under what exact circumstances does an agent know that some agent has sent a message? When can a sender be assured that all others have received the message?

In previous work, we have studied such questions in a 3-agent version of the protocol [2]. Our approach was to model the protocol as a knowledge-based program and to use epistemic model checking as a tool to help us identify precisely the conditions under which an agent obtains some types of knowledge of interest. The approach helped us to identify some unexpected situations in which relevant knowledge is obtained. We recap the definition of knowledge-based programs and our formulation of the 2-phase protocol as a knowledge-based program in the following sections, after which we study this knowledge-based program further using the abstraction developed above.

## 8 Implementation of Knowledge-based Programs

Knowledge-based programs [9] are like standard programs, except that expressions may refer to an agent’s knowledge. That is, in a knowledge-based program for agent  $i$ , we may find statements of the form “ $v := \phi$ ”, where  $\phi$  is a formula of the logic of knowledge, i.e., a boolean combination of atomic formulas concerning the agent’s observable variables and formulas of the form  $K_i\psi$ .

Unlike standard programs, knowledge-based programs cannot in general be directly executed, since the satisfaction of the knowledge subformulas depends on the set of all runs of the program, which in turn depends on the satisfaction of these knowledge subformulas. This apparent circularity is handled by treating a knowledge-based program as a specification, and defining when a concrete standard program satisfies this specification. We give a formulation of the semantics of knowledge-based programs tailored to the programming language of the present paper.

Suppose that we have a concrete program  $P$  of the same syntactic structure as the knowledge-based program  $\mathbf{P}$ , in which each knowledge-based expression  $\phi$  is replaced by a concrete predicate  $p_\phi$  of the local variables of the agent. Starting at an initial Kripke Structure  $M_0$ , the concrete program  $P$  generates a set of runs that form the worlds of a Kripke Structure  $M_0[P]$ . We now say that  $P$  is an *implementation of the knowledge-based program  $\mathbf{P}$  from  $M_0$*  if for each joint action  $A$  in the program  $P$ , corresponding to a joint action  $\mathbf{A}$  in the knowledge-based program, if we write  $P = P_0; A; P_1$ , where  $P_0$  and  $P_1$  are programs, then for each knowledge condition  $\phi$  occurring in  $\mathbf{A}$ , we have  $M_0[P_0] \models p_\phi \Leftrightarrow \phi$ . That is, the concrete condition is equivalent to the knowledge condition in the implementation at each point in the program where it is used. (In a more general formulation, where knowledge conditions may contain temporal operators, knowledge-based programs may have no implementations, a behaviourally unique implementation, or many implementations, but for the restricted language we consider it can be shown that there is a unique implementation.)

We now describe a partially automated process, using epistemic model checking, that can be followed to find implementations of knowledge-based programs  $\mathbf{P}$ . The user begins by introducing a local boolean variable  $v_\phi$  for each knowledge formula  $\phi = K_i\psi$  in the knowledge-based program, and replacing  $\phi$  by  $v_\phi$ . Treating  $v_\phi$  as a “history variable”, the user may also add to the program statements of the form  $v_\phi := e$ , relying on their intuitions concerning situations under which the epistemic formula  $\phi$  will be true. This produces a standard program  $P$  that is a candidate to be an implementation of the knowledge-based program  $\mathbf{P}$ . (It has, at least, the correct syntactic structure.) To verify the correctness of  $P$  as an implementation of  $\mathbf{P}$ , the user must now check that the variables  $v_\phi$  are being maintained so as to be equivalent to the knowledge formulas that they are intended to express. This can be done using epistemic model checking, where we verify formulas of the form  $v_\phi \Leftrightarrow K_i\psi$  at points in the program where the condition  $\phi$  is used.

In general, the user’s guess concerning the concrete condition that is equivalent to the knowledge formula may be incorrect, and the model checker will

report the error. In this case, the model checker can be used to generate an *error trace*, a partial run leading to a situation that falsifies the formula being checked. The next step of our process requires the user to analyse this error trace (by inspection and human reasoning) in order to understand the source of the error in their guess for the concrete condition representing the knowledge formula. As a result of this analysis, a correction of the assignment(s) to the variable  $v_\phi$  is made by the user (this step may require some ingenuity on the part of the user.) The model checker is then invoked again to check the new guess. This process is iterated until a guess is produced for which all the formulas of interest are found to be true, at which point an implementation of the knowledge-based program has been found. We refer the reader to our previous work [2] for further discussion and examples of the application of this iterative process. (We deemphasize the process in the present paper, and focus on the results.)

## 9 The Two-phase Broadcast Protocol as a Knowledge-based Program

We now give a formulation of Chaum's two-phase protocol (see Section 7) as a knowledge-based program, and discuss the associated verification conditions. (The knowledge-based program is similar to that given in our earlier work, but includes some improvements.)

We assume that there are  $n$  agents, and  $Agt = \{1..n\}$ . Figure 3 represents the 2-phase protocol by giving a knowledge-based program for agent  $i$ . The local variable `slot-request`, assumed to be defined in the structure from which the program is run, records the slot number (in the range 1..n) that this agent will attempt to reserve. If `slot-request=0`, then the agent will not attempt to reserve any slot. The variable `message`, also assumed to be defined, records the single bit message that the agent wishes to anonymously broadcast (if any). The program introduces the variables `rcvd0` and `rcvd1`, as well as a variable `dlvrd`. (Additional new variables, are implicit in the instances of  $DC_i$ .)

The term `conflict(s)` in the knowledge-based program represents that there is a conflict on slot  $s$ . This is a global condition that is defined as

$$\text{conflict}(s) = \bigvee_{i \neq j} (i.\text{slot-request} = s = j.\text{slot-request}) .$$

i.e., there exist two distinct agents  $i$  and  $j$  both requesting slot  $s$ .

The term `sender( $i, x$ )` represents that an agent is sending message  $x$ . Thus, the variable `rcvd0` is assigned to be true if the agent learns that someone is trying to send the bit 0, and similarly for `rcvd1[s]`. However, there are some subtleties in the implementation that lead us to consider two distinct versions of the program. In one version, called *strong reception*, we use the definition

$$\text{sender}(i, x) = \bigvee_{j \neq i} (j.\text{message} = x \wedge j.\text{slot-request} \neq 0) .$$

```

Pi = {
local variables:
  slot-request: [0..n],
  message: Bool,
  rcvd0, rcvd1, dlvrđ: Bool;
//reservation phase
for (s = 1; s ≤ n; s++)
{
  DCi(slot-request=s);
}
//transmission phase
for (s = 1; s ≤ n; s++)
{
  DCi(if (slot-request = s ∧ ¬Ki(conflict(s))
  then message
  else false) );
}
rcvd0:= Ki(sender(i,0));
rcvd1 := Ki(sender(i,1));
dlvrđ:= ∧x∈Bool((message = x ∧ slot-request ≠ 0) ⇒
                Ki(∧j≠i Kjsender(j,x)))
}

```

**Figure 3: The knowledge-based program *CDC***

That is, we take an agent to have received the bit 0 if it knows that *some other* agent is sending the message  $x$ . In the other, that we refer to as *weak reception*, we define

$$\text{sender}(i, x) = \bigvee_j (j.\text{message} = x \wedge j.\text{slot-request} \neq 0) .$$

That is, we take an agent to have received the bit 0 if it knows that *some* agent is sending the message  $x$ , possibly itself. Since an agent always knows its own message  $x$ , it trivially knows  $\text{sender}(i, x)$  if it is trying to send a message (i.e.,  $i.\text{slot-request} \neq 0$ ), so this may seem very weak. However, since other agents may consider it possible that the agent is not seeking to send a message, we see that it becomes of greater interest in the context of an agent's knowledge of delivery of its message, represented by the assignment for the variable  $\text{dlvrđ}$ .

We note that this representation of the 2-phase protocol as a knowledge-based program is *speculative*: an agent transmits in a slot so long as it does not know that there is a conflict. This allows that a collision will occur during the transmission phase.

Since an agent may attempt to reserve a slot, and then back off, or may send in a reserved slot without success because of a collision during the transmission phase, the protocol does not guarantee that the message will be delivered. In this case, the agent is required to retry the transmission in the next run of the protocol. So that it can determine whether a retry is necessary, the final



assignment to the variable `dlvrd` captures whether the agent knows that its (anonymous) transmission has been successful. this assignment captures that the transmission is successful if the agent knows that the other agents know that some agent is sending its message. We similarly refer to *weak delivery* and *strong delivery* depending on which version of the predicate `sender(i, x)` is used.<sup>3</sup>

We remark that the knowledge-based program is interpreted with respect to the assumption of perfect recall, and implementations may make use of history variables to capture observations that the agent makes during the running of the protocol. Thus, by placing the reception and delivery assignments at the end of the program (rather than just after each DC instance), we ensure that the agents are able to behave optimally by making use of all information they gather during the running of the program. As we discuss below, this allows us to capture some subtle sources of information.

In Figure 4, we give the generic structure of a possible implementation of the knowledge-based program, as we seek using our partially-automated process. The variable `kc[s]` is used to represent the epistemic condition concerning conflict in the knowledge-based program (i.e.,  $\neg K_i(\text{conflict}(\mathbf{s}))$ ). Thus, in verifying that we have an implementation, the key condition to be checked is whether `kc[s]`  $\Leftrightarrow \neg K_i(\text{conflict}(\mathbf{s}))$  just after this variable is assigned. The main difficulty in finding an implementation is to find the appropriate concrete assignment (to take the place of the “???”) for this variable that will make this condition valid. Similarly we seek assignments to the variables `rcvd0[s]`, `rcvd1[s]` that give these the intended meaning.

We note that each of the instances of the protocol  $DC_i$  introduces additional variables, which may be used in the concrete predicates we substitute for the “???”. In particular, they introduce round result variables, which we denote by `rr[t]` for  $t \in \{1..2n\}$ . Here `rr[t]` represents the round result variable from the  $t$ -th instance of  $DC_i$  in the implementation. The implementations also introduce key variables  $k_e$  and  $b$ , which need to be separated in the different instances: we may similarly use  $k_e[t]$  and  $b[t]$  to denote the  $t$ -th instance of such a variable.

We now discuss the formulas that are used to verify the implementation. As discussed above, these conditions need to be verified at specific stages of the program, viz., the step before the occurrence of the knowledge formula of interest.

The first formula of interest concerns the correctness of the guess for the knowledge condition  $\neg K_i(\text{conflict}(\mathbf{s}))$  (in case of the speculative implementation, or  $K_i(\neg \text{conflict}(\mathbf{s}))$  (in the case of the conservative implementation). In the implementation, this condition is represented by the variable `kc[s]`.

*Specification 1: `kc[s]` correctly represents knowledge of the existence of a conflict in slot  $s = 1..3$ .*

$$i.\text{kc}[\mathbf{s}] \Leftrightarrow \neg K_i(\text{conflict}(\mathbf{s})) \quad (1)$$

<sup>3</sup> We remark that in case of weak delivery, replacing the expression  $\bigwedge_{j \neq i} K_j \text{sender}(j, x)$  by  $\bigwedge_j K_j \text{sender}(j, x)$  in the assignment to `dlvrd` would have no effect, since in the weak case it always holds that  $(i.\text{message} = x \wedge i.\text{slot-request} \neq 0) \Rightarrow K_i(\text{sender}(i, x))$ .

```

Pi = {
local variables:
    slot-request: [0..n],
    message: Bool,
    rcvd0, rcvd1, dlvr: Bool,
    kc[n]: Bool;
//reservation phase
for (s = 1; s ≤ 3; s++)
{
    DCi(slot-request == s);
}
//transmission phase
for (s = 1; s ≤ n; s++)
{
    kc[s] := ???;
    DCi(if (slot-request == s ∧ kc[s])
        then message
        else false);
}
rcvd0 := ???;
rcvd1 := ???;
dlvr:= ???
}

```

**Figure 4: A generic implementation of CDC**

Next, the protocol has some positive goals, viz., to allow agents to broadcast some information, and to do so anonymously. Successful reception of a bit is intended to be represented by the variables `rcvd0` and `rcvd1`. To ensure that the assignments to these variables correctly implement their intended meaning in the knowledge-based program, we use specifications of the following form.

*Specification 2: reception variables correctly represent transmissions by others*

$$i.\text{rcvd0} \Leftrightarrow K_i(\text{sender}(i, 0)) \quad (2a)$$

and

$$i.\text{rcvd1} \Leftrightarrow K_i(\text{sender}(i, 1)) \quad (2b)$$

Similarly, we need to verify correct implementation of the agent's knowledge about whether its transmission is successful.

*Specification 3: delivery variables correctly represent knowledge about delivery*

$$\begin{aligned}
i.\text{dlvr} &\Leftrightarrow \bigwedge_{x \in \text{Bool}} (i.\text{message} = x \wedge i.\text{slot-request} \neq 0 \\
&\Rightarrow K_i(\bigwedge_{j \neq i} K_j \text{sender}(j, x)))
\end{aligned}$$

There are strong and weak versions of Specifications 2 and 3, depending on the choice for `sender`( $i, x$ ).

Finally, the aim of the protocol is to ensure that when information is transmitted, this is done anonymously. An agent may know that one of the other two

agents has a particular message value, but it may not know what that value is for a specific agent. We may write the fact that agent  $i$  knows the value of a boolean variable  $x$  by the notation  $\hat{K}_i(x)$ , defined by  $\hat{K}_i(x) = K_i(x) \vee K_i(\neg x)$ . Using this, we might first attempt to specify anonymity as  $\bigwedge_{j \neq i} (\neg \hat{K}_i(j.\text{message}))$ , i.e., agent  $i$  knows no other’s message. Unfortunately, the protocol cannot be expected to satisfy this: suppose that all agents manage to broadcast their message and all messages have the same value  $x$ : then each knows that the other’s value is  $x$ . We therefore write the following weaker specification of anonymity:

*Specification 4: The protocol preserves anonymity*

$$\bigvee_{x=0,1} K_i \left( \bigwedge_{j \neq i} (j.\text{message} = x) \right) \vee \bigwedge_{j \neq i} (\neg \hat{K}_i(j.\text{message})) .$$

This is checked at the very end of the protocol.

## 10 Model Checking Performance

To verify the specifications for the knowledge-based program in a putative implementation, we have applied the epistemic model checker MCK [10]. We refer the reader to our previous work [2] for a description of some of the particularities of how this is done. Since the details are straightforward, we focus here on how the abstraction developed in this paper impacts the performance of model checking.

We would like to verify whether a putative implementation  $P$  implements the knowledge-based program  $\mathbf{P}$  from an initial structure  $M_0$ . This requires that we model check the formulas from the previous section. Since these formulas concern only the initial variables of the agents, and variables introduced outside the scope of the  $DC_i$  calls, it follows from Theorem 2 that we may verify instead whether these formulas hold at appropriate times during the running of the abstract program  $P^a$  that we obtain by replacing each instance of  $DC_i$  in  $P$  by  $DC_i^a$ .

We have performed some experiments in which we use MCK for this model checking problem. MCK is a symbolic model checker, and model checking a formula involves first building a symbolic (Binary Decision Diagram [15]) representation of the model itself, and then using this representation in the construction of a symbolic representation of the situations where the particular formula of interest is false. All specifications are checked using the perfect recall interpretation of knowledge and the model checking algorithm for this semantics which is described in [22] (which is flagged by `spec_spr_xn` in MCK). To estimate individual formula timings, we deduct model construction times (estimated by the time to model check the specification True), from the actual time for model checking each specification (which includes model construction and formula verification time.) All experiments are conducted on a PC with Intel(R) Xeon(R) 4 × 3 GHz, and 16 GB memory, using MCK 0.1.1. Where the execution crashed due to a memory error, we report “x” in the tables.

Our methodology for identifying an implementation of the knowledge-based program requires that we perform model checking on number of different approximations to the final implementation, and, when a specification fails, using the counter-example found to revise the approximation. Table 1 gives the runtimes for the initial program, in which we guess the predicate False for the implementation of all knowledge formulas in the knowledge-based program. For each specification  $x$  we give runtimes for model checking the specification in the concrete program and the abstract program (indicated by  $x^a$ ). We count the cost of verifying all instances of the specification required to check the correctness of the implementation at different times where the knowledge condition occurs in the program. (With  $n$  agents, we need to check Specification 1 at  $n$  locations in the implementation, but specifications 2-4 just once.) As we improve the approximation, the program becomes more complex, and the model checking runtimes increase. In Table 2 we give the runtimes for the final approximation, in which we have identified a program that is verified as implementing the knowledge-based program.

$n$			Specification							
	Model	Model <sup>a</sup>	1	1 <sup>a</sup>	2	2 <sup>a</sup>	3	3 <sup>a</sup>	4	4 <sup>a</sup>
3	0.4	0.24	43	5	5880	41	6100	4	6300	5
4	29.15	4.2	x	34	x	68	x	69	x	70
5	x	63	x	4800	x	5400	x	5500	x	5544

**Table 1.** Model Checking Runtimes (seconds)– initial approximation

$n$			Specification							
	Model	Model <sup>a</sup>	1	1 <sup>a</sup>	2	2 <sup>a</sup>	3	3 <sup>a</sup>	4	4 <sup>a</sup>
3	0.45	0.4	50	16	7200	127	7350	34	7400	18
4	135	6	x	167	x	378	x	251	x	252
5	x	74	x	1096	x	1957	x	1979	x	1998

**Table 2.** Model Checking Runtimes (seconds) – final implementation

For a more detailed indication of the impact of the abstraction, Table 3 compares the runtimes for model checking the anonymity specification (Specification 4) in the concrete and abstract programs for the final implementation after a given number of rounds of the Dining Cryptographers Protocol. Note that the maximum number of rounds of Dining Cryptographers in the 2-phase protocol is twice the number of agents.

In all these experiments, the runtimes obtained indicate that the abstraction results in a significant decrease of runtimes, (in some cases of several orders

Agents	version	Rounds									
		1	2	3	4	5	6	7	8	9	10
3	concrete	0.6	0.9	2.2	18	335	7350	-	-	-	-
3	abstract	0.5	0.6	0.7	1.6	3.1	17.8	-	-	-	-
4	concrete	340	575	587	1478	2661	x	x	x	-	-
4	abstract	9	11	11.2	11.7	32	85	86	249	-	-
5	concrete	x	x	x	x	x	x	x	x	x	x
5	abstract	91	110	133	134	183	311	752	722	950	1990

**Table 3.** Model Checking Runtimes (seconds) for Specification 4

of magnitude) and helps to bring problems of larger scale (in particular, with larger numbers of agents and greater numbers of rounds of the basic Dining Cryptographers protocol) within the bounds of feasibility of model checking.

## 11 Implementations of the knowledge-based program

Using the optimization obtained from the abstraction, we have been able to extend our previous analysis of the knowledge-based program in the 3-agent case to the cases of 4 and 5 agents, gaining more insight into the  $n$ -agent case for general  $n$ . We now describe the implementations we found for the program, which demonstrate that the protocol contains some further subtle flows of information beyond those we found in the 3 agent case.

One point worth noting is that, in addition to providing an optimization of epistemic model checking, our abstraction result also provides information that is useful in the search for an implementation of the knowledge-based program. Observe that the variables  $k_e$  do not occur in the abstract version of the protocol, nor in the formulas we need to check to verify an implementation. Thus, in guessing a concrete predicate to be substituted for one of the knowledge conditions, we can confine our attention to predicates that do not contain the  $k_e$  variables. Indeed, since  $i.b$  is computed from information already at agent  $i$ 's disposal, we need only consider predicates based on agent  $i$ 's initial information and the round result variables  $rr[k]$ .

The first knowledge condition we need to implement, for Specification 1, is  $\neg K_i \text{conflict}(s)$ . Plainly, one situation where an agent knows that there is a conflict is when it attempts to reserve a slot and the round result for the reservation is not 1. (So an even number of agents attempted to reserve the slot.) Thus, one potential implementation for  $\neg K_i \text{conflict}(s)$  is the assignment  $kc[s] := \neg(\text{slot-request} = s \wedge rr[s] = 0)$ . Model checking Specification 1 for this predicate at the point of the  $s$ -th transmission confirms in all of the cases  $n = 3, 4, 5$  that this captures the knowledge condition  $\neg K_i \text{conflict}(s)$  exactly at this point: there are no other ways that the agent can know of a conflict on a slot before transmitting on it, besides seeing a reservation clash. (In particular, previous transmissions do not contain any relevant information.)

It is interesting to consider not just the knowledge condition  $\neg K_i \text{conflict}(s)$  that occurs in the program, but also the stronger condition  $K_i \neg \text{conflict}(s)$  (the formula  $K_i \neg p \Rightarrow \neg K_i p$  is a validity of the logic of knowledge). For example, if an agent who is broadcasting on a slot knows that all other agents know the slot is conflict free, then it knows that its message will be delivered. Thus, we have also added a local variable  $\text{conflict-free}(s)$  to the implementation, for  $s = 1 \dots n$ , and sought assignments to this variable that satisfy the formula  $i.\text{conflict-free}(s) \Leftrightarrow K_i \neg \text{conflict}(s)$ . This turns out to be quite a subtle matter.

To express this condition, it is useful to introduce a formula  $C_0 = x$  where  $x \in \{0, \dots, n\}$  to express that the number of 0's obtained as round results in the reservation phase is  $x$ . We may then note the following situations in the protocol in which  $K_i \neg \text{conflict}(s)$  holds.

- If  $C_0 = 0$  or  $C_0 = 1$ , then the agent knows there is no conflict on any slot. Note that in this case there are at least  $n - 1$  agents who are requesting the at least  $n - 1$  distinct slots with reservation round result 1, leaving at most one further agent. If this agent had requested any of the slots with round result 1, this would have caused a 2-way reservation clash, contradicting the observed round result of 1. Hence this agent did not request any slot, and *all* slots are conflict-free.
- If  $C_0 \geq 2$ , then in general, an agent cannot determine whether or not there is a conflict on any of the reserved slots, since there may be a 3-way clash on one of these slots. However, in the particular case where  $C_0 = 2$  and the agent itself does not request any slot ( $\text{slot-request} = 0$ ) then  $n - 2$  agents are accounted for by the  $n - 2$  slots on which we see a reservation round result of 1, and the remaining one agent cannot be assigned to any slot without changing the round result, and hence the count. Hence this agent cannot be requesting a slot, and the agent knows that all slots are conflict-free.
- Note that if  $C_0 = 2$  or  $C_0 = 3$ , and the agent requests a slot but detects a collision at slot reservation time, then there must have been at least 2 agents requesting this slot, leaving at most  $n - 2$  agents for the  $n - 1$  other slots, where we see either  $n - 3$  or  $n - 4$  slots with reservation result of 1. This means at least  $n - 1$  or  $n - 2$  agents are accounted for in total, so the number of agents remaining to contribute to a further collision on the remaining  $n - 1$  other slots is at most 1. This agent can not be assigned to any slot without changing the round result for that slot, so it must not be requesting a slot. Thus, all the other  $n - 1$  slots are collision free.
- The above cases use information from the reservation phase. Agents may also be able to deduce that slots are conflict-free as a result of information they obtain during the transmission phase. If  $C_0 = 2$  or  $C_0 = 3$ , the agent requests a slot and obtains a reservation round result of 1 for this slot, but then detects a collision at transmission time, then there must have been at least a 3-way collision on that agent's slot, and by a similar argument to the previous case, we deduce that all the other slots are collision free.

These conditions may be captured by the assignment

$$\begin{aligned}
i.\text{conflict-free}(s) &:= C_0 = 0 \vee C_0 = 1 \vee (C_0 = 2 \wedge i.\text{slot-request} = 0) \vee \\
&((C_0 = 2 \vee C_0 = 3) \wedge \bigvee_{t=1}^n (s \neq t \wedge i.\text{slot-request} = t \wedge \text{rr}[t] = 0)) \vee \\
&((C_0 = 2 \vee C_0 = 3) \wedge \bigvee_{t=1}^n (s \neq t \wedge i.\text{slot-request} = t \wedge \text{rr}[t] = 1 \\
&\quad \wedge \text{rr}[n+t] \neq i.\text{message}))
\end{aligned}$$

The above formula states several concrete conditions under which the agent knows there is no conflict on a particular slot  $s$ . We have verified by model checking that for  $n = 3, 4$ , and  $5$  that, at the end of the protocol, for all slots  $s$  we have  $i.\text{conflict-free}(s) \Leftrightarrow K_i \neg \text{conflict}(s)$ , and conjecture that it holds for all  $n$ .

We remark that in the case of  $C_0 = 0$  or  $C_0 = 1$ , this information is available to all agents, and it is common knowledge<sup>4</sup> that all slots are conflict free. In the other cases, collision freedom on a slot may be known to some agents but not to others. For example, consider the situation with  $n = 4$  and where the **slot-request** and **message** values and round results are given as in Figure 5(a). Here agent 2 sees a reservation collision and two 1's elsewhere, so knows that slots 1 and 4 are collision free. However, agent 1 does not know this, since the scenario of Figure 5(b) is consistent from its viewpoint, and here there is a collision on slot 4.

(a)	$i:$	1	2	3	4	(b)	$i:$	1	2	3	4
	$i.\text{slot-request}$	4	3	1	3		$i.\text{slot-request}$	4	1	1	1
	$i.\text{message}$	1	0	1	0		$i.\text{message}$	1	1	1	1
	$\text{rr}[i]$	1	0	0	1		$\text{rr}[i]$	1	0	0	1
	$\text{rr}[4+i]$	1	0	0	1		$\text{rr}[4+i]$	1	0	0	1

**Figure 5:** Collision Freedom is not Common Knowledge

As mentioned above, we consider in this paper a speculative version of the knowledge-based program, in which an agent transmits its message in its requested slot  $s$  in the transmission phase if  $\neg K_i \text{conflict}(s)$ . One could also study a *conservative* version, where an agent only transmits if  $K_i \neg \text{conflict}(s)$ . The analysis above shows that this would lead to a much more complicated implementation<sup>5</sup>, where, moreover, the agent would transmit only in the low probability case when almost all other agents also have a message to send, and they happen to pick distinct slots!

Returning to the implementation of the speculative version, we need to find the appropriate assignments to the variables `rcvd0`, `rcvd1` and `dlvrd`, for which

<sup>4</sup> A fact is common knowledge [13] if all agents know it, all agents know that all other agents know it, and so on for all levels of iteration of knowledge.

<sup>5</sup> For a number of reasons, including the fact that we need an implementation of the knowledge condition at all transmission steps, rather than just at the end of the protocol, the above condition is not yet adequate for such an implementation.

we have strong and weak versions.

**Strong Version:** In this case, reception of a bit  $x$  means that the agent knows that some other agent is sending that bit  $x$ . An obvious situation where this is the case is where the agent is not itself sending in the slot, the reservation round result is 1, and the bit  $x$  is observed as the round result in the corresponding transmission slot. Note that there may still be a collision on that slot, but since the number of agents in the collision is then odd, at least one must be sending  $x$ . As we noted in our previous work [2], there is another, less obvious, situation when an agent can know that another agent is sending a bit  $x$  in a slot, viz., when the agent is itself transmitting bit  $y$  in that slot and observes that the round result for the transmission is the compliment of  $y$ . Since the number of other agents in the conflict must be even, there must be both another agent sending 0 and another agent sending 1 in the slot. We have verified by model checking in the case of 3-5 agents that with the assignment

$$i.\text{rcvdx} := \bigvee_{s=1}^n ((i.\text{slot-request} \neq s \wedge \text{rr}[s] = 1 \wedge \text{rr}[n+s] = x) \vee (i.\text{slot-request} = s \wedge \text{rr}[s] = 1 \wedge \text{rr}[n+s] \neq i.\text{message}))$$

Specification 2 is satisfied in the strong version.

For the delivery condition, we have verified that the assignment

$$\begin{aligned} \text{dlvrd} := & (\text{slot-request} \neq 0 \wedge (C_0 = 0 \vee C_0 = 1)) \vee \\ & (\text{slot-request} \neq 0 \wedge \text{message} = 1 \wedge \\ & \quad \bigvee_{s \neq t, s, t=1..n} (\text{rr}[s] = \text{rr}[t] = 1 \wedge \text{rr}[n+s] = \text{rr}[n+t] = 1)) \vee \\ & (\text{slot-request} \neq 0 \wedge \text{message} = 0 \wedge \\ & \quad \bigvee_{s \neq t, s, t=1..n} (\text{rr}[s] = \text{rr}[t] = 1 \wedge \text{rr}[n+s] = \text{rr}[n+t] = 0)) \end{aligned}$$

works for Specification 3 in the strong version for the cases  $n=3-5$ . The intuitions for this formula are as follows. In the case  $C_0 = 0 \vee C_0 = 1$ , as discussed above, it is common knowledge that all slots are conflict-free, so all transmissions are guaranteed to be delivered. As just noted, an agent who is not sending on a slot receives the value transmitted on that slot. However, an agent sending on a slot, and not noticing a clash on the transmission, considers it possible that there are other agents transmitting the very same value on that slot, and these will not know that there is another agent transmitting on the slot. However, if there are at least two distinct reserved slots where that value is transmitted, then each receives the value from some slot other than the one on which it transmits. This is expressed in the remainder of the formula.

**Weak Version:** In the weak interpretation, we require only that a receiver learn that someone, possibly themselves is sending a message. The problem of undetected collisions in the transmission phase does not arise here, and the implementation is more straightforward. We have verified in the 3-5 agent settings that the following assignments work:

$$\text{rcvdx} := (\text{slot-request} \neq 0 \wedge \text{message} = x) \vee \bigvee_{s=1}^n (\text{rr}[s] = 1 \wedge \text{rr}[n+s] = x)$$



$$\text{dlvrd} := \text{slot-request} \neq 0 \wedge \bigvee_{s=1}^n (\text{rr}[s] = 1 \wedge \text{rr}[n+s] = \text{message})$$

Intuitively, in this case, an agent’s own message counts as a delivery, and messages observed on reserved slots can be taken at face value.

Finally, the anonymity property, Specification 4, has been verified to hold in all the implementations obtained from the assignments discussed above, when  $n = 3 - 5$ .

## 12 Related Work

Abstractions of the kind we have studied, relating a protocol involving a trusted third party to a protocol that omits the trusted third party, are often used in theoretical studies to specify the objectives of a multi-party protocol. One example where this is done in a formal methods setting is work by Backes et al [1], who study the abstraction of pi- calculus programs based on multi-party computations. Where we consider a model checking approach to verification, with an expressive epistemic specification language, they use a type-checking approach. Their notion of abstraction is richer than the bisimulation-based approach we have taken, in that they also deal with probabilistic and computational concerns. However, as we have noted, we are interested in the preservation of a set of epistemic properties (nested knowledge formulas) that is richer in some dimensions than is usually considered in this literature. Our abstraction result could be easily strengthened to incorporate probability, as was done for a secure channel abstraction by van der Meyden and Wilke [23]. However computational complexity issues mesh less well with epistemic logic, and developing a satisfactory solution to this remains an open problem.

Epistemic model checking is less developed than model checking for temporal logic, and many possible optimization techniques remain to be explored for this field. Other approaches using abstraction in the context of epistemic model checking include [6, 5]. These works are orthogonal to ours in that where we are concerned with an abstraction of a particular primitive (the Dining Cryptographers protocol), that works for all formulas, they are concerned with symmetry reductions or deal with a more general class of programs than we have considered, but need to restrict the class of formulas preserved by the abstraction.

Other model checkers for the logic of knowledge are under development but MCK remains unique in supporting the perfect recall semantics for knowledge using symbolic techniques. DEMO [24] implicitly deals with perfect recall, but is based on a somewhat different logic (epistemic update logic), and uses explicit state model checking techniques, so it is not clear if it could be used for the type of analysis and scale of programs we have considered in this paper. MCMAS [17], MCTK [21] and VERICS [7] are based on the observational semantics for knowledge (which is also supported in MCK).

It is possible in some cases to represent the perfect recall semantics using the observational semantics (essentially by encoding all history variables into

the state) and this approach is used in [18] to analyse the same 2- phase protocol as we considered in this paper. However, this modelling is ad-hoc and the transformation from perfect recall to observational semantics is handled manually, making it susceptible to missing timing channels if not done correctly. (Moreover, we did briefly experiment with such a modeling for the large programs studied in this paper, but found that the perfect recall model checking algorithms outperform the observational semantics model checking algorithm on these programs.) The work of [18] does not view the protocol as a knowledge-based program, as we have done, nor do they consider abstraction.

Knowledge-based programs have been applied successfully in a number of applications such as distributed systems, AI, and game theory. They have been used in papers such as [8, 12, 14, 3, 19] in order to help in the design of new protocols or to clarify the understanding of existing protocols. Examples of the development of standard programs from knowledge-based programs can be found in [20, 8, 16]. The approach described in these papers is different from the one we discussed here in that it is done by pencil and paper analysis and proof. Examples of the use of epistemic model checkers to identify implementations of knowledge-based programs remain limited. One is the work of Baukus and van der Meyden [3] who use MCK to analyze several protocols for the cache coherence problem using knowledge-based framework.

The 2-phase protocol has been implemented in the Herbivore system [11], which elaborates it with protocols allowing agents to enter and exit the system, as well as grouping agents in anonymity cliques for purposes of efficiency. Variants of the protocol have also been considered by Pfitzman and Waidner [25]. These would make interesting case studies for future applications of our approach.

### 13 Conclusion

We have established the soundness of an abstraction for of protocols based on the Dining Cryptographers, and applied this result to optimize epistemic model checking of protocols that use Dining Cryptographers as a primitive. Our experimental results clearly demonstrate that the abstraction yields efficiency gains for epistemic model checking in interesting examples. In particular, we have used these gains to extend an analysis of a knowledge-based program for the 2-phase protocol, and derived some interesting conclusions about the subtle information flows in the protocol. Several research directions suggest themselves as a result of this work. One is to complete the analysis of the knowledge-based program for all numbers of agents. We conjecture that our present implementation can be shown to work for all numbers of agents, and it would be interesting to have a proof of this claim: this would have to be done manually rather than by model checking, unless an induction result can be found for the model checking approach. Another direction is to consider richer extensions of the 2-phase protocol, addressing issues such as messages longer than a single bit, agent entry and exit protocols, as well as adversarial concerns such as collusion, cheating and disruption of the protocol. We hope to address these in future work.

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