

Operational and Epistemic Approaches to Protocol Analysis: Bridging the Gap

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Abstract. Operational models of protocols, on one hand, are readable and conveniently match their implementation, at a certain abstraction level. Epistemic models, on the other hand, are appropriate for specifying knowledge-related properties such as anonymity. These two approaches to specification and analysis have so far developed in parallel and one has either to define ad hoc correctness criteria for the operational model or use complicated epistemic models to specify the operational behavior. We work towards bridging this gap by proposing a combined framework which allows modeling the behavior of a protocol in a process language with an operational semantics and supports reasoning about properties expressed in a rich logic with temporal and epistemic operators.

1 Introduction

Knowledge-related aspects are currently being recognized as very relevant when expressing and analyzing correctness requirements of complex distributed algorithms and communication protocols, from the fundamental ones like consensus in a network, to applications like information flow control and security protocols (secrecy, anonymity, fair exchange). Many approaches based on epistemic logics have been developed for the analysis of such protocols: BAN logic [8], the theory of function views [20], interpreted systems [14,16,25] etc.

They allow for natural and effective representations of subtle effects of communication acts such as classified information leaking to attackers or participants gaining the common knowledge that the protocol they were running meets its goal. But on the other hand, modeling protocols using epistemic-logic-based approaches requires a high degree of expertise and verification of functional properties is often very complex. The information updates generating the transitions between epistemic states are especially tedious to specify, because logics are geared to expressing properties rather than operational steps of a protocol.

The operational behavior of protocols is, however, easily and conveniently specified in languages such as process algebras [7,22,2] and message sequence charts [9]. Functional requirements such as liveness and safety are then easily verified by model checking applied on the underlying transition systems. Unfortunately, these standard and successful verification schemes use temporal logics

that are not well-suited for expressing knowledge-related properties, therefore complex specialized solutions need to be sought in order to make process algebras suitable for the analysis of epistemic-flavored properties like anonymity [26,11]. See [20,13] for a more detailed comparison of epistemic-based vs. process-based protocol verification.

In this paper, we propose a framework that allows one to benefit the best of the two worlds, i.e., one can specify the behavior of a protocol in a process language and verify properties expressed in a logic with both temporal and epistemic operators. To achieve this, the key idea is to introduce explicit identities in our process language PAi and allow every action to be annotated with a visibility range — i.e., a set of identities that may observe it and a “public appearance” — i.e., an alternative action that is observed by the identities outside the visibility range. We give an operational semantics for PAi in terms of annotated labeled transition systems (ALTSs), which are LTSs with, for every identity, an extra indistinguishability relation on states. These relations model the uncertainties of the identities (typically principals in a protocol) about the current state, similar to the way uncertainties are represented in standard possible-world semantics for epistemic logics [14]. Thanks to the combination of transitions and indistinguishability relations, ALTSs naturally support verification of logic formulae containing both temporal and epistemic operators. We introduce a rich logic, $E\overline{\mu}$ (epistemic μ -calculus with past) and give it an interpretation on ALTSs.

Due to the explicit use of identities, PAi allows a precise specification of the information hiding behavior within protocols, and it is therefore more expressive and flexible than traditional process algebras. It is also more intuitive and more formal than epistemic logics, when it comes to behavior modeling. Also $E\overline{\mu}$ is more expressive than the usual temporal logics used in traditional protocol verification. The resulting model checking framework $PAi+E\overline{\mu}$ soundly extends the traditional process-based and epistemic model checking settings.

Related Work. The fact that the two verification approaches, process algebraic and epistemic, are complementary and that they should ideally be combined has already been recognized in [20], where the aim is, just as here, to provide a framework in which both protocol specification and correctness criteria can be specified succinctly and intuitively (and the authors indeed put the two approaches in sharp contrast). They introduce the notion of *function view* to represent partial information and uses it to precisely formalize several subtle information hiding properties. Since the focus of that theory is proper formalization of requirements, we believe that it is complementary to ours and that it could possibly be used in our PAi models, for defining suitable visibility ranges.

BAN-logic [8], designed for the analysis of authentication in security protocols, is very popular, but it is a known problem that a clear semantics, linking the high-level BAN-specification to runs of the protocol, is still missing. Also in other interesting recent work concerning Dynamic Epistemic Logic [15,3,19] with an operational flavor, just as in tool-supported temporal epistemic approaches [25,18], where existing temporal specification languages are used, but the embedding of the epistemic aspects remains (for a large part) informal. We

start from the other side - a process specification language with a formal semantics, and work towards properly integrating epistemic aspects.

Interpreted Systems [14,25,16] are close to the operational semantics of our process language. In fact, it is possible to translate ALTSs to ISs. Our key improvement is the introduction of a process specification language with a formal semantics, which enables the modeling of systems at a reasonable abstraction level. In [16], interpreted systems are used to model different complex notions of (probabilistic) anonymity, using also an epistemic logic. Our approach is related to and complements that one, by providing a way of verifying, on process-based specifications, anonymity notions as defined by [16].

The concept of indistinguishability used here bears resemblances to the data independence technique in [6]. We consider runs of a protocol indistinguishable if they appear equal to a principal (as defined by the visibility range of actions). It is worthwhile to extend our framework along the lines of [6], by allowing the visibility range of actions to be dynamically updated.

Concurrently with our work, a rich language C^3 [5] and a powerful logic CPL [21] have been developed for analyzing cryptographic protocols. The aim there is integrating a wide range of features, from deontic and spatial operators to probabilities, in one unified setting. C^3+CPL is therefore very expressive, but complex and seems difficult to implement, while our basic language with an easy to grasp operational semantics can immediately lead to a practical verification toolset. In fact, a prototype implementation already exists [1]. Furthermore, there is a fundamental difference between our underlying logics: that of [21] is a state-based logic (à la LTL) and ours is action-based (à la modal μ -calculus).

Overview. Section 2 introduces our generic process language for specifying protocols and a transition-system semantics for it. Section 3 defines our temporal epistemic logic $E\bar{\mu}$ and the interpretation of $E\bar{\mu}$ formulas on the transition systems. Then we show that this construction does indeed bridge the gap between process-based and epistemic-logic-based approaches to protocol analysis, by proving that its projections on the two worlds are consistent with established definitions in the two worlds separately (Section 4). Section 5 shows an example and Section 6 concludes the paper and presents directions for future research.

2 *PAi*: Syntax and Operational Semantics

In this section, we present the syntax and the operational semantics of a simple modeling language which we call process algebra with identities (*PAi*). *PAi* has generic features, that can be adapted to match constructs of any classical operational modeling language (such as CCS [22], CSP [7] or Spi-Calculus [2]). It mostly resembles Milner's CCS, but we deviate from CCS in a few ways. Apart from adding identities, we use sequential composition instead of action prefixing (and thus, we also introduce a termination predicate), since this is very handy in writing protocol specifications. Also, we do not hide the result of a communication automatically and leave this, if at all desired, to the renaming

function since the communicated message can be of relevance in the correctness specification of the protocol.

PAi : Syntax. Let \mathcal{Act} be a finite set of *action names* which will be ranged over by $a, b, a_0, ?a, !a, \dots$, and let \mathcal{Id} be a finite set of *identities* typically denoted by $i, j, \dots i_1, i_2, \dots$. We designate an action $\tau \in \mathcal{Act}$ to denote the internal (silent) action; in addition to its common process-algebraic meaning, an internal action here represents a message that offers no new information to the observer principal. Question mark and exclamation mark (preceding actions) represent the receiving and the sending parts of a communication, respectively, and an action without such marks is the outcome of the communication.

$$\begin{aligned} Proc &::= 0 \mid D \mid Proc; Proc \mid Proc + Proc \mid Proc \parallel Proc \\ D &::= (J)\alpha \end{aligned}$$

0 denotes inaction (the process that has terminated). $d = (J)\alpha \in D$ denotes a decorated action and has the following intuitive meaning: action $\alpha \in \mathcal{Act}$ is taken and is visible to principals $i \in J \subseteq \mathcal{Id}$, while principals $j \notin J$ observe $\rho(\alpha)$ being taken, where $\rho : \mathcal{Act} \rightarrow \mathcal{Act}$ is a global renaming function, which assigns to every action its “public appearance”. The renaming function ρ should be defined by the specifier of a protocol but we assume that $\rho(\tau)$ is always defined to be τ . For any other action a , if $\rho(a) = \tau$, then $(J)a$ becomes unobservable to the principals not in J . The combination of identity annotations on actions and the action renaming provides different views on the behavior of the system, according to different principals. Modeling passive observation of a system by hiding parts of it to specific principals is already done in the literature [26], but we will generate the views for all principals simultaneously. This enables talking about properties such as “ i knows that j knows that k has communicated message a ”. $Proc; Proc$ denotes sequential composition, $Proc + Proc$ denotes nondeterministic choice, and $Proc \parallel Proc$ denotes parallel composition.

Example 1. Take $P = (1)a; (1, 2)d + (1)b + (1)c$, with the renaming function $\rho(a) = \rho(b) = \rho(c) = dum$ where dum is a dummy basic action and over the identity set $\mathcal{Id} = \{1, 2\}$. P denotes the process that executes one of the actions a, b, c , but only principal 1 is aware of the exact action taking place. 1 is the principal making a choice between actions a, b and c , and 2 is an observer who only notices that a choice has been made, but not what the outcome was. This is a process-style formalization of the *private communication* from epistemic modeling, where a party learns something while other parties are watching and learn that the party learned something, but not precisely what. After the first step, the process terminates or, if the first step was a , continues with the execution of d . Since principal 2 is allowed to observe the execution of d , she may now conclude that the first step must have been a , although 2 was not actually allowed to observe the a . This is exactly the type of information leaks that we aim at capturing with our verification framework.

PAi : Operational Semantics. We introduce the notion of *Annotated Labeled Transition Systems* (ALTS) as labeled transition systems extended with

$$\begin{array}{c}
 \text{(o)} \frac{}{(0, \pi)\checkmark} \quad \text{(a)} \frac{}{(d, \pi) \xrightarrow{d} (0, \pi \frown d)} \quad \text{(s0)} \frac{(x_0, \pi) \xrightarrow{d} (y_0, \pi')}{(x_0; x_1, \pi) \xrightarrow{d} (y_0; x_1, \pi')} \\
 \text{(s1)} \frac{(x_0, \pi)\checkmark \quad (x_1, \pi) \xrightarrow{d} (y_1, \pi')}{(x_0; x_1, \pi) \xrightarrow{d} (y_1, \pi')} \quad \text{(s2)} \frac{(x_0, \pi)\checkmark \quad (x_1, \pi')\checkmark}{(x_0; x_1, \pi'')\checkmark} \\
 \text{(n0)} \frac{(x_0, \pi) \xrightarrow{d} (y_0, \pi')}{(x_0 + x_1, \pi) \xrightarrow{d} (y_0, \pi')} \quad \text{(n2)} \frac{(x_0, \pi)\checkmark}{(x_0 + x_1, \pi')\checkmark} \quad \text{(p0)} \frac{(x_0, \pi) \xrightarrow{d} (y_0, \pi')}{(x_0 \parallel x_1, \pi) \xrightarrow{d} (y_0 \parallel x_1, \pi')} \\
 \text{(p2)} \frac{(x_0, \pi)\checkmark \quad (x_1, \pi')\checkmark}{(x_0 \parallel x_1, \pi'')\checkmark} \quad \text{(p3)} \frac{(x_0, \pi) \xrightarrow{(J)^2 a} (y_0, \pi') \quad (x_1, \pi) \xrightarrow{(J')^1 a} (y_1, \pi'')}{(x_0 \parallel x_1, \pi) \xrightarrow{(J \cup J')^a} (y_0 \parallel y_1, \pi \frown (J \cup J')^a)} \\
 \hline
 \text{(= refl)} \frac{}{\pi \stackrel{i}{=} \pi} \quad \text{(= } \rho 0) \frac{\pi \stackrel{i}{=} \pi' \quad a = b \quad i \in J \cap J'}{\pi \frown (J)a \stackrel{i}{=} \pi' \frown (J')b} \\
 \text{(= } \rho 1) \frac{\pi \stackrel{i}{=} \pi' \quad \rho(a) = \rho(b) \quad i \notin J' \cup J}{\pi \frown (J)a \stackrel{i}{=} \pi' \frown (J')b} \quad \text{(= } \rho 2) \frac{\pi \stackrel{i}{=} \pi' \quad a = \rho(b) \quad i \in J \setminus J'}{\pi \frown (J)a \stackrel{i}{=} \pi' \frown (J')b} \\
 \text{(= } \tau 0) \frac{\pi \stackrel{i}{=} \pi' \quad i \notin J \quad \rho(a) = \tau}{\pi \frown (J)a \stackrel{i}{=} \pi'} \quad \text{(= } \tau 2) \frac{\pi \stackrel{i}{=} \pi'}{\pi \frown (J)\tau \stackrel{i}{=} \pi'} \\
 \hline
 \text{(strip)} \frac{(x, \pi) \xrightarrow{(J)^a} (y, \pi')}{(x, \pi) \xrightarrow{a} (y, \pi')} \quad \text{(I)} \frac{\pi_0 \stackrel{i}{=} \pi_1}{(x_0, \pi_0) \cdot \dots \cdot (x_1, \pi_1)}
 \end{array}$$

Fig. 1. SOS of PAi

annotations that denote when two states are deemed indistinguishable from the viewpoint of a principal, based on the actions taken so far. This is determined by the information that a principal receives in the course of protocol execution, which in turn is determined by the visibility annotations.

Definition 1 (ALTS). An ALTS is a 5-tuple $\langle St, \rightarrow, \checkmark, I, s_0 \rangle$, where St is the set of operational states, $\rightarrow \subseteq St \times Act \times St$ is the transition relation, $\checkmark \subseteq St$ is the termination predicate, $I \subseteq St \times Id \times St$ is the indistinguishability relation and s_0 is the initial state.

For readability, we denote statements $(s, l, s') \in \rightarrow$, $s \in \checkmark$ and $(s, i, s') \in I$ by $s \xrightarrow{l} s'$, $s\checkmark$ and $s \stackrel{i}{\cdot} \cdot s'$, respectively, for each $s, s' \in St$, $l \in Act$ and $i \in Id$. The transition relation \rightarrow has exactly the same role and meaning as in the standard notion of LTS. Formula $s\checkmark$ means that in state s it is possible to terminate. Expression $s_0 \stackrel{i}{\cdot} \cdot s_1$ denotes that the principal with identity i cannot distinguish s_0 from s_1 since both s_0 and s_1 are reachable through paths that look identical as far as as principal i can observe and distinguish. It is desirable for $\stackrel{i}{\cdot} \cdot$ to be an equivalence relation for each $i \in Id$ since this leads to a natural representation of knowledge (i.e., S5 Kripke models in modal logic, see [14]).

In Figure 1, we associate ALTS's to PAi processes by means of a semantics in the SOS style of [24]. The operational state of PAi is a pair (p, π) where $p \in Proc$ is a PAi process and π is a finite sequence of decorated actions recording the perception of the process gathered so far. First we define auxiliary relations $\xrightarrow{d} \subseteq St \times St$ and $\stackrel{i}{\equiv} \subseteq D^* \times D^*$ for each decorated action d and identity i . Transition relation \xrightarrow{d} defines transitions among operational states labeled with decorated action d and $\stackrel{i}{\equiv}$ defines when two traces are deemed indistinguishable by principal i . Note that each process p in the state (p, π) has one past trace π and possibly many futures. That is why, for example, in the deduction **(p3)** both parallel arguments x_0 and x_1 are assumed to start from the same history π , which is the common history of $x_0 \parallel x_1$. In the deduction rule **(strip)**, we strip off the extra information on the labels (concerning the visibility range) and apply encapsulation (leaving out individual send and receive actions) and obtain the transition relation \rightarrow . (We could have used an explicit restriction operator but decided not to do so to keep the presentation simple.) Deduction rule **(I)** lifts the concept of indistinguishability from traces to operational states. We omitted symmetric rules **(n1)**, **(n3)**, **(p1)**, **(p4)**, **(=ρ3)**, **(=τ1)**, and **(=τ3)**. Termination of a process is orthogonal to its past history, so we use different meta-variables for the traces in the premises and the conclusion of rules **(s2)**, **(n2)**, and **(p2)**. The transition relation \Rightarrow and indistinguishability relation \cdots are the sets of all closed statements provable using the deduction rules (plus their symmetric versions) from Figure 1. The semantics of a process p is defined by the ALTS with pairs of processes and decorated traces as states, \rightarrow as transition relation, \checkmark as termination relation, \cdots as indistinguishability relation, and (p, \square) as the initial state, where \square denotes the empty sequence of decorated actions. The following lemma states that $\stackrel{i}{\equiv}$ is an equivalence relation. We intentionally did not add deduction rules to enforce symmetry and transitivity of $\stackrel{i}{\equiv}$ explicitly in order to preserve the inductive structure of our SOS specification.

Lemma 1. *Relation $\stackrel{i}{\equiv}$ is an equivalence relation.*

3 An Epistemic Mu-Calculus

We introduce an epistemic mu-calculus with past ($E\bar{\mu}$) which combines temporal, epistemic, and fixed point constructs. We give our logic an interpretation on the operational model introduced in Section 2.

Syntax. The syntax of $E\bar{\mu}$ is given by the following grammar:

$$\phi ::= \top \mid X \mid \phi \wedge \phi \mid \neg\phi \mid \langle a \rangle \phi \mid \langle \bar{a} \rangle \phi \mid K_i \phi \mid \nu X. \phi(X)$$

(if X occurs only positively in ϕ),

where a ranges over the set of actions ($a \in Act$). Then $\langle a \rangle \phi$ stands for “after some execution of a , ϕ holds”; $\langle \bar{a} \rangle \phi$ has the same intuition as $\langle a \rangle \phi$, except that it refers to the *past*, i.e., there is a state in which ϕ holds and from which it is possible to take an a -step to the current state. $K_i \phi$ should be read as “principal

i knows that ϕ holds”. The greatest fixed point operator $\nu X.\phi(X)$ is used to define recursive concepts. It intuitively means that the current state is in the largest set X of states that satisfy $\phi(X)$. (Here X is a variable ranging over propositional formulas, which can be identified by the sets of states in which such a formula is true. This is made formal by introducing valuations, but we leave this correspondence informal here.) For convenience, we define and use the following abbreviations for commonly used logical formulae:

$[a]\phi$	i.e., $\neg\langle a\rangle\neg\phi$ and intuitively means that after <i>all</i> a -transitions, ϕ holds.
$\mu X.\phi(X)$	(with X occurring positively in ϕ) is the least fixed point operator, which is defined by $\neg\nu X.\neg\phi(\neg X)$ (X also occurs positively in $\neg\phi$). The current state is in the smallest set of states satisfying $\phi(X)$.
$\langle\cdot\rangle\phi$	(similarly, $\langle\bar{\cdot}\rangle\phi$) stands for $\bigvee_{a\in Act}\langle a\rangle\phi$ ($\bigvee_{a\in Act}\langle\bar{a}\rangle\phi$), which is by itself an abbreviation for a finite number of disjunctions. Intuitively, it means that after (before) <i>some</i> transition ϕ holds.
$\uparrow a$	(similarly, a^\uparrow) is an abbreviation for $\mu X.\langle a\rangle\top \vee \langle x\rangle.X$ (or $\mu X.\langle\bar{a}\rangle\top \vee \langle\bar{x}\rangle.X$). So, it is possible to reach a state in the future where an a -transition is possible (or go back to a state in the past that results from an a -transition).
$[\cdot^*]\phi$	(similarly, $[\bar{\cdot}^*]\phi$) is an abbreviation for $\mu X.\phi \vee [\cdot]X$ (or $\mu X.\phi \vee [\bar{\cdot}]X$). The intuition behind this abbreviation is that all future paths will (paths in the past) lead to a state, in which there is a state satisfying ϕ . ($\langle\cdot^*\rangle\phi$ and $\langle\bar{\cdot}^*\rangle\phi$ are defined accordingly.)
$C_J\phi$	stands for $\nu X.(\bigwedge_{i\in J} K_i(X \wedge \phi))$ [14], meaning: “it is common knowledge among the principals in the set J that ϕ holds”.

Common knowledge is a very powerful construction, expressing that agents in J not only know that ϕ holds, but also that all agents in J know that ϕ holds, and that all agents in J know that all agents in J know that ϕ holds, and so on. This property has so far not been amenable to specification and verification with standard operational techniques, while it is in fact very interesting, particularly for protocols where trust is an issue. Common knowledge can express, for instance, that participants in a multiparty fair exchange protocol trust each other and the protocol they are running. Let $E\bar{\mu}$ -forms denote the set of $E\bar{\mu}$ formulae.

Interpreting $E\bar{\mu}$ Formulas on ALTSS. We now define what it means for a formula $\phi \in E\bar{\mu}$ -forms to be satisfied in the ALTSS A .

Definition 2 (satisfaction). Let $A = \langle S, \rightarrow, \checkmark, I, s_0 \rangle$ be an ALTSS. The satisfaction relation \models for formulae $\phi \in E\bar{\mu}$ -forms is defined inductively as follows:

$A, s \models \top$	<i>iff</i>	<i>true</i>
$A, s \models \phi_1 \wedge \phi_2$	<i>iff</i>	$A, s \models \phi_1$ and $A, s \models \phi_2$
$A, s \models \neg\phi$	<i>iff</i>	$A, s \models \phi$ is not true
$A, s \models \langle a\rangle\phi$	<i>iff</i>	there is an $s' \in S$ s.t. $s \xrightarrow{a} s'$ and $A, s' \models \phi$
$A, s \models \langle\bar{a}\rangle\phi$	<i>iff</i>	there is an $s' \in S$ s.t. $s' \xrightarrow{\bar{a}} s$ and $A, s' \models \phi$
$A, s \models K_i\phi$	<i>iff</i>	for all reachable $s' \in S$ s.t. $s \cdot^i \cdot s' : A, s' \models \phi$
$A, s \models \nu X.\phi(X)$	<i>iff</i>	$s \in \bigcup\{S' \subseteq S \mid \forall s' \in S'. A, s' \models \phi(X := S')\}$

A satisfies a formula ϕ , denoted $A \models \phi$, if $s_0 \models \phi$.

The most noticeable of the rules above is the one for $K_i\phi$. It expresses the fact that i knows ϕ if ϕ holds in all states considered possible by i when residing in s , that is in all states belonging to the $\cdot^i\cdot$ equivalence class of s . The semantic rules in the previous section constructed this relation based on what i was allowed to observe from the run of the protocol. The intention behind the formula $K_i\phi$ is not to check what i learned in terms of explicit information the principal received (e.g., as contents of some message), but what i learned through observation. Observation (partial observation) of what actually happens, can reduce a principal's uncertainties and thereby 'leak' information. Particularly, if principles are familiar with the protocol, they may derive from certain actions taking place, that the previous action must have been a particular one, even if they did not know it before. This is the case in the example depicted in Figure 2, where principal 2 learns from observation of action d , that the choice made before must have been a . More exactly, sequences of actions which are not properly protected by the visibility restrictions ρ may lead to a refinement of the $\cdot^i\cdot$ class which is sufficient for i to distinguish between a state where agent's j secret key is 100 and a state where agent j 's secret key is 200, even if i never participated in a direct communication over j 's key. This process of learning by the refinement of the indistinguishability relations along the traces is captured in the definition of $A, s \models K_i\phi$. Our logic satisfies the standard axioms for a logic of knowledge:

Theorem 1. *The so-called S5 axioms (cf. [14, p.59]) hold in $E\bar{\mu}$:*

$$\begin{array}{ll} \mathbf{K} : K_i\phi \wedge K_i(\phi \rightarrow \psi) \rightarrow K_i\psi & \mathbf{4} : K_i\phi \rightarrow K_iK_i\phi \quad (\text{positive introspection}) \\ \mathbf{T} : K_i\phi \rightarrow \phi \quad (\text{reflexivity}) & \mathbf{5} : \neg K_i\phi \rightarrow K_i\neg K_i\phi \quad (\text{negative introspection}) \end{array}$$

The definition of satisfaction provides a model checking algorithm, that will be decidable on the finite trees generated by the semantics of our PAi . Since the $E\bar{\mu}$ satisfaction relation on ALTSs rests on classically accepted definitions for similar but less expressive models, we expect that it should be possible to reuse and extend existing efficient model checking tools.

An interesting and non-trivial question is to find a behavioral equivalence that is characterized by $E\bar{\mu}$. We expect the answer to be some notion of bisimilarity that considers both \xrightarrow{a} and $\cdot^i\cdot$ as transition relations. Due to the presence of past temporal operators, we may have to resort to some notion of bisimilarity that takes backward steps also into account (a notion of forward-backward or history-preserving bisimilarity).

4 Bridging the Gap: Relation to Existing Theories

In this section we show that the framework introduced in this paper is a conservative extension of the traditional process theoretic modeling on the one hand, and epistemic modeling on the other hand. To this end, we prove that the satisfaction relation defined in Section 3 preserves the standard satisfaction relations of $\bar{\mu}$ (μ -calculus with past) formulae on labeled transition systems and of E

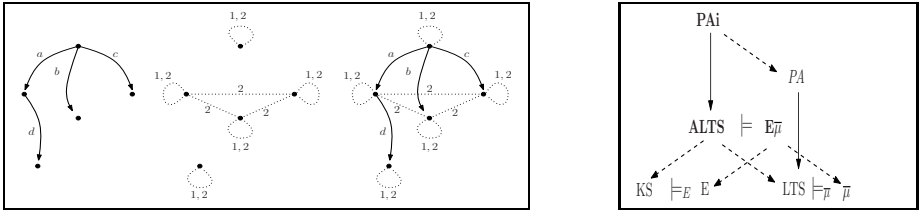


Fig. 2. Left picture: An ALTS A (rightmost), together with its projections: 'the temporal part' $lts(A)$ (leftmost) and 'the epistemic part' $em(A)$ (center). In $lts(A)$, the points are *states*, the arrows are *transitions*. In $em(A)$, points are *possible worlds* and lines are *indistinguishability* relations labeled with identities of agents. In (A) , the points are states and possible worlds simultaneously. Both temporal and epistemic relations are present. The epistemic valuation in a state is given by the actions executed from the initial state to that state. In the initial state, combined temporal epistemic formulae hold like $\langle a \rangle (K_1 a^{\uparrow} \wedge \neg K_2 a^{\uparrow})$ — expressing that after an a -action, it is known to principal 1 that action a has been executed, but 2 doesn't know that. However, 2 knows that one of the actions a, b, c has been executed ($\langle a \rangle (K_2 (a^{\uparrow} \vee b^{\uparrow} \vee c^{\uparrow}))$). More interestingly, after step d is executed, 2 has learned that a must have been the first step: $\langle a \rangle \langle d \rangle K_2 a^{\uparrow}$. Modeling this phenomenon of agents learning facts that were never explicitly told to them is exactly the power of epistemic logic approaches, that we took over in the combined framework. **Right picture:** Projecting into process-theoretic domain and epistemic domain. A dashed arrow $x \dashrightarrow y$ means that x is an extension of y . The arrow $x \rightarrow y$ means y is the semantic model of x . The links between ALTS, LTS, KS, $E\bar{\mu}$, $\bar{\mu}$, E are discussed in this paper. The connection with the process languages PAi and PA (a pure process theoretic formalism) is explained in [12].

(epistemic logic) formulae on Kripke structures. In Figure 2, the left picture illustrates the three semantic models discussed in this section: the existing LTS and KS, and the newly introduced ALTS. The right picture gives an overview of the connections between the various notions.

Projecting into the Process-Theoretic Domain. A Labeled Transition System (LTS) is a standard semantic domain for process-theoretic formalisms. Formally, an LTS over a set of labels L is a tuple $\langle St, \rightarrow, \checkmark, s_0 \rangle$, where St is the set of operational states, $\rightarrow \subseteq St \times L \times St$ is the transition relation, $\checkmark \subseteq St$ is the termination predicate and s_0 is the initial state. It typically represents the behavior of a reactive system in terms of states and transitions. Then requirements formulated in a temporal logic are matched against this behavior in the process of model checking.

A very general logical language to reason about processes is the μ -calculus with past ($\bar{\mu}$) [23], which is obtained by leaving out the knowledge construct $K_i \phi$ from the syntax of our logic presented in Section 3. That a state s in the LTS $T = \langle S, \rightarrow, \checkmark, s_0 \rangle$ satisfies a $\bar{\mu}$ formula ϕ (denoted $T, s \models_{\bar{\mu}} \phi$) is defined inductively as follows:

$$\begin{array}{ll}
T, s \models_{\bar{\mu}} \top & \text{iff true} \\
T, s \models_{\bar{\mu}} \neg\phi & \text{iff } T, s \not\models_{\bar{\mu}} \phi \\
T, s \models_{\bar{\mu}} \phi_1 \wedge \phi_2 & \text{iff } T, s \models_{\bar{\mu}} \phi_1 \text{ and } s \models_{\bar{\mu}} \phi_2 \\
T, s \models_{\bar{\mu}} \langle a \rangle \phi & \text{iff exists } s' \in S, \text{s.t. } s \xrightarrow{a} s' \text{ and } T, s' \models_{\bar{\mu}} \phi \\
T, s \models_{\bar{\mu}} \langle \bar{a} \rangle \phi & \text{iff exists } s' \in S, \text{s.t. } s' \xrightarrow{\bar{a}} s \text{ and } T, s' \models_{\bar{\mu}} \phi \\
T, s \models_{\bar{\mu}} \nu X. \phi(X) & \text{iff } s \in \bigcup \{S' \subseteq S \mid \forall s' \in S'. T, s' \models_{\bar{\mu}} \phi(X := S')\}
\end{array}$$

We prove that the ALTS + $E\bar{\mu}$ model checking framework properly extends the LTS + $\bar{\mu}$ model checking framework, in the sense that whatever was possible in the latter, is still possible and has the same meaning in the former. This is witnessed by the fact that LTS + $\bar{\mu}$ can be immediately obtained by simply stripping the ALTS from the I relations and the $E\bar{\mu}$ logic from the epistemic operator K_i . The following theorem formalizes this.

Theorem 2. *Consider a PAi process p and the ALTS $A = \langle St, \rightarrow, \surd, I, s_0 \rangle$ obtained as semantics of (p, \square) by following the SOS rules in Figure 1. Let (q, π) be a state in A , reachable from (p, \square) (i.e. in the transitive closure of \rightarrow from $s_0 = (p, \square)$). Let us define $\text{lts}(A) = (St, \rightarrow, \surd, s_0)$. Then, for each $\bar{\mu}$ formula ϕ , $A, (q, \pi) \models \phi$ iff $\text{lts}(A), q \models_{\bar{\mu}} \phi$.*

This means that for purely temporal aspects of correctness, one can safely ignore the epistemic aspects of our semantics and our logic.

Projecting into the Epistemic Domain. Epistemic logics are mainly concerned with expressing subtle properties of communication acts, related to the knowledge, beliefs and intentions of communicating parties. In standard epistemic logic (following [17]), epistemic properties are validated in static rich snapshots of communications (*epistemic models*), that don't express the temporal evolution of the system. The language of epistemic logic with common knowledge defined by:

$$\phi ::= p \mid \neg\phi \mid \phi_1 \wedge \phi_2 \mid K_i\phi \mid C_J\phi$$

Here the p comes from a given set of propositional variables $\mathcal{P}rop$. These propositions represent the atomic facts the agents may know about. The subscript i ranges over a given set of agents \mathcal{I} , and J over subsets of \mathcal{I} . The standard reading of the epistemic modalities K_i and C_J is the same as ours in the previous section: “ i knows that...” and “it is common knowledge among the agents in J that...”, respectively.

An *epistemic (S5-)model* is a Kripke structure $\langle W, \{R_i \mid i \in \mathcal{I}\}, V \rangle$, where W is a nonempty set of possible worlds, R_i is an equivalence relation on W for each $i \in \mathcal{I}$, and $V : \mathcal{P}rop \rightarrow \mathcal{P}(W)$ is a valuation function assigning to each propositional variable the set of worlds in which it holds. Given an epistemic model M and world $s \in W$, satisfaction (\models_E) is defined recursively as follows:

$$\begin{array}{ll}
M, s \models_E p & \text{iff } s \in V(p) \\
M, s \models_E \neg\phi & \text{iff it is not true that } M, s \models_E \phi \\
M, s \models_E \phi_1 \wedge \phi_2 & \text{iff } M, s \models_E \phi_1 \text{ and } M, s \models_E \phi_2 \\
M, s \models_E K_i\phi & \text{iff for all } M, s' \in W, \text{ if } sR_i s' \text{ then } M, s' \models_E \phi \\
M, s \models_E C_J\phi & \text{iff for all } M, s' \in W, \text{ if } s(\cup_{i \in J} R_i)^* s' \text{ then } M, s' \models_E \phi
\end{array}$$

To isolate ‘the epistemic part’ of our framework, we make suitable choices for the set of propositions, and the set of agents. In the context of our *PAi*-processes we associate with every action $a \in \mathcal{Act}$ a proposition \underline{a} (which can be read as “ a has been executed sometime before”), and we let $\mathcal{Prop} := \{\underline{a} \mid a \in \mathcal{Act}\} \cup \{\top\}$. Furthermore, we let \mathcal{I} be our set of identities \mathcal{Id} . We call the resulting logic E .

We can then say that our modeling and verification framework is also conservative when it comes to purely epistemic aspects. Namely, if we restrict the ALTS associated with a *PAi* process to the I relations, we obtain an epistemic model where purely epistemic formulas hold exactly when they hold in the original ALTS, according to the $E\bar{\mu}$ satisfaction relation. Let us define an embedding $\mathcal{E} : E\text{-forms} \rightarrow E\bar{\mu}\text{-forms}$ of formulas into $E\bar{\mu}$ formulas, by taking $\mathcal{E}(\underline{a}) = a^\dagger$ and extending from there:

$$\begin{aligned} \mathcal{E}(\top) &= \top & \mathcal{E}(\phi_1 \wedge \phi_2) &= \mathcal{E}(\phi_1) \wedge \mathcal{E}(\phi_2) \\ \mathcal{E}(\underline{a}) &= a^\dagger & \mathcal{E}(K_i\phi) &= K_i\mathcal{E}(\phi) \\ \mathcal{E}(\neg\phi) &= \neg\mathcal{E}(\phi) & \mathcal{E}(C_J\phi) &= \nu X.(\bigwedge_{i \in J} K_i(X \wedge \phi)). \end{aligned}$$

The following theorem formally expresses the conservativeness of $E\bar{\mu}$ w.r.t. E .

Theorem 3. *Consider a PAi process p over the set of actions \mathcal{Act} . Let $A = \langle St, \rightarrow, \checkmark, I, s_0 \rangle$ be the ALTS obtained as semantics of (p, \square) by following the SOS rules in Figure 1. Let us define its associated epistemic model as $em(A) = \langle St, \{\cdot^i \mid i \in \mathcal{Id}\}, V \rangle$, with propositions from \mathcal{Prop} , $V(\underline{a}) = \{s \in St \mid A, s \models \mathcal{E}(\underline{a})\}$ and $V(\top) = St$. Then for any E formula ϕ and any possible world $s \in St$, $A, s \models \mathcal{E}(\phi)$ iff $em(A), s \models_E \phi$.*

5 An Example Protocol: Dining Cryptographers

In order to illustrate the relative advantages of the combined framework compared to using exclusively the operational approach or the epistemic one, we discuss the Dining Cryptographers protocol [10], which has already been independently and extensively analyzed using both operational [26,4] and epistemic approaches [20,16,25]. The story, a metaphor for anonymous broadcast, is about three cryptographers having dinner together. The bill is paid anonymously by one of them, or by the National Security Agency (NSA). They respect each other’s right to anonymity, but they wish to find out whether the payer was NSA or not. To this end, they come up with the following protocol: each neighboring pair of cryptographers generates a shared bit, by flipping a coin; then each cryptographer computes the exclusive or (XOR) of the two bits she sees, then announces the result — or the flipped result, if she was herself the payer. The XOR of the three publicly announced results indicates whether the payer was an insider or NSA.

Model. A model of this protocol in our process language is shown in Figure 3. Inspired by the input construction in the algebraic specification language μCRL , we use $\sum_{x:\{x_1 \dots x_n\}} P(x)$ as an abbreviation for $P(x_1) + \dots + P(x_n)$, where $\{x_1 \dots x_n\}$ is a finite set and $P(x_i)$ denotes the process expression $P(x)$ in which x_i has been substituted for x .

$$\begin{array}{l}
\mathit{Crypt}(i) \quad = \sum_{b:\mathit{Bool}} ((i)?\mathit{pay}(i, b); \mathit{CryptFlip}(i, b)) \\
\mathit{CryptFlip}(i, b) \quad = \sum_{c:\mathit{Bool}} ((i)\mathit{flip}(i, c); \mathit{CryptShare}(i, b, c)) \\
\mathit{CryptShare}(i, b, c) \quad = \sum_{d:\mathit{Bool}} (((i)!\mathit{share}(i \bmod 3 + 1, c) \parallel (i)?\mathit{share}(i, d)); \\
\quad \quad \quad \mathit{CryptBcast}(i, b, c, d)) \\
\mathit{CryptBcast}(i, b, c, d) \quad = ((i)!\mathit{bcast}(i, b \oplus c \oplus d); (i)!\mathit{bcast}(i, b \oplus c \oplus d)) \\
\quad \parallel \sum_{x, y:\mathit{Bool}} (((i)?\mathit{bcast}(i + 1 \bmod 3 + 1, x) \\
\quad \parallel (i)?\mathit{bcast}(i \bmod 3 + 1, y)); \\
\quad \quad \quad \mathit{nsa}(i, -(b \oplus c \oplus d \oplus x \oplus y))) \\
\mathit{Master} \quad = \quad (\mathbf{M})!\mathit{pay}(1, \top); (\mathbf{M})!\mathit{pay}(2, \perp); (\mathbf{M})!\mathit{pay}(3, \perp) \\
\quad + (\mathbf{M})!\mathit{pay}(1, \perp); (\mathbf{M})!\mathit{pay}(2, \top); (\mathbf{M})!\mathit{pay}(3, \perp) \\
\quad + (\mathbf{M})!\mathit{pay}(1, \perp); (\mathbf{M})!\mathit{pay}(2, \perp); (\mathbf{M})!\mathit{pay}(3, \top) \\
\quad + (\mathbf{M})!\mathit{pay}(1, \perp); (\mathbf{M})!\mathit{pay}(2, \perp); (\mathbf{M})!\mathit{pay}(3, \perp)
\end{array}$$

Fig. 3. A PA_i model of The Dining Cryptographers protocol. \oplus denotes exclusive or.

The model is rather close to the CSP description presented in [26], the only significant difference being that the actions are annotated with identities from the set $\mathcal{Id} = \{1, 2, 3, \mathbf{M}\}$. Note that the parameters used in the basic actions and process definitions are just generic names for the concrete instances resulting from instantiating them. For example, $?pay(i, b)$ is not defined in our process language but rather it stands for a number of instances such as $?pay(1, \top)$, $?pay(i, \perp)$ each of which are basic actions (obtained by globally replacing i and b with a member of \mathcal{Id} and $\{\perp, \top\}$ in the process definition each time). The behavior of the i th cryptographer is specified by the process $\mathit{Crypt}(i)$ and the behavior of the whole DC system as a parallel composition of $\mathit{Crypt}(i)$'s and the Master process, $DC_3 = \mathit{Crypt}(1) \parallel \mathit{Crypt}(2) \parallel \mathit{Crypt}(3) \parallel \mathit{Master}$. A cryptographer process executes a series of actions corresponding to the three big steps of the protocol: decide whether to pay or not, flip the coins together with the neighbors, and announce the result of XOR-ing the two coins and her own paying bit. The first step is modeled as a statement $pay(i, b)$, which is in fact a communication step with the Master . The second step is modeled by the processes $\mathit{CryptFlip}(i)$ and $\mathit{CryptShare}(i)$. In other existing models [26,4], the shared coins are represented by separate processes, but in order to keep the specification simple, we merge the behavior of the i th coin with the behavior of the i th cryptographer. Therefore, process $\mathit{Crypt}(i)$ will execute a flip action and then share the result with the right-hand neighbor, by executing an action $!\mathit{share}$ which will synchronize with the $?share$ from the next cryptographer in the ring. $\mathit{CryptBcast}$ models the last phase, announcing the result of one's computation ($!\mathit{bcast}$), receiving the results from all the others ($?bcast$) and concluding for itself that NSA paid or not ($\mathit{nsa}(i, \top)$, $\mathit{nsa}(i, \perp)$).

The renaming function ρ specifies how much of a cryptographers' actions is visible for observing parties. For any $i \in \{1, 2, 3\}$ and $b \in \{\top, \perp\}$, we define $\rho(\mathit{pay}(i, b)) = \mathit{pay}(i)$, $\rho(\mathit{bcast}(i, b)) = \mathit{bcast}(i, b)$, $\rho(\mathit{share}(i, c)) = \mathit{share}(i)$, $\rho(\mathit{flip}(i, b)) = \mathit{flip}(i)$ and $\rho(\mathit{nsa}(i, b)) = \mathit{nsa}(i, b)$, where $\mathit{pay}(1)$, $\mathit{bcast}(1, \top)$, \dots are basic actions.

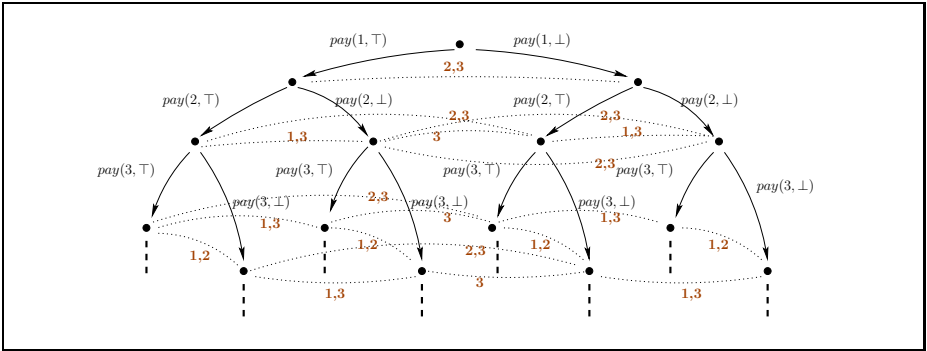


Fig. 4. A small fragment from the ALTS generated for the DC specification. For readability, we omitted some $\overset{i}{\dots}$ relations generated by reflexivity and transitivity.

Analysis. Figure 4 shows the top part of the ALTS generated by the rules in Figure 1 from the process specification in Figure 3. We check relevant functional and epistemic properties of this protocol by matching $E\bar{\mu}$ formulas against this ALTS, as dictated by the satisfaction relation \models (Definition 2).

First of all, we can check functional correctness, by asking for instance that in all executions where one of the cryptographers paid, the action $nsa(1, \top)$ is eventually observable, meaning that the first cryptographer draws the right conclusion that the payer was an insider. This requirement is a purely temporal formula, for each $i \in \{1, 2, 3\}$: $[pay(i, \top)] \bigwedge_{j \in \{1, 2, 3\}} [.*] nsa(j, \perp)$.

Better yet, we can also check the powerful epistemic statement that “everybody knows that the payer is an insider” eventually becomes common knowledge among the three cryptographers. This is expressed as: for every $i \in \{1, 2, 3\}$, it holds that $[pay(i, \top)] [.*] C_{\{1, 2, 3\}} (\bigwedge_{j \in \{1, 2, 3\}} nsa(j, \perp))^{\uparrow}$.

Anonymity, the main goal of the protocol, is not expressible as a purely temporal property, but it is conveniently expressible as a temporal epistemic property. The anonymity of cryptographer i (holding in the initial state of our model) is expressed by the formula $[pay(i, \top)] \bigwedge_{j \in \{1, 2, 3\} \setminus \{i\}} \neg \langle .* \rangle K_j (pay(i, \top))^{\uparrow}$. All these properties are satisfied by our PAi model, according to the satisfaction relation \models defined in Section 3.

Comparison to Other DC Models. PAi allows a simple and operational modeling, just as intuitive as any other process language, see also for instance a CSP model [26] and a pi-calculus model [4] of the Dining Cryptographers. All these models are definitely closer to the protocol description than logic models [18,25] and moreover, they are supported by a semantics which formally links the description of a protocol to its actual behavior model.

On the other hand, epistemic logic models allow expressing and checking anonymity as epistemic formulae, which is much more natural than the equivalence checking method employed in the process theoretic approach. More precisely, operational approach to verification of anonymity requires writing down

new descriptions for each anonymity property that has to be checked, because these properties are dependent on the point of view of the observer. In the ALTS that our specification generates, all points of view are simultaneously present, thus a direct and natural (epistemic) verification is possible.

6 Conclusion

Motivated by protocols and properties where much importance is given to the participating entities and not only to the actual evolution of the system — like certain security protocols, information flow — we presented a simple process language where the concept of *identity* is explicitly present. We gave it an operational semantics in terms of an extended form of labeled transition systems and defined a satisfaction relation for properties expressed in a rich logic combining temporal and epistemic operators. The result is a specification and verification framework that combines the best parts of two complementary approaches to protocol analysis: process algebras and epistemic logics.

Our framework is particularly suitable for modeling and verification of protocols on top of authenticated secret channels, ensured for instance by a Public Key Infrastructure. In these protocols, the security threats typically do not come from an external intruder controlling the communication channels, but from the participants themselves. Examples are protocols for fair exchange, voting, auctions, anonymity. In security protocols with cryptography or active attackers, some behavioral choices are determined by the current knowledge of the principals. In particular, a principal can distinguish more traces by gaining access to keys. To properly accommodate this, our framework should be extended, possibly by allowing dynamic update of indistinguishability relation in the course of protocol execution. Note however that the current framework is just as powerful in modeling cryptography aspects as any other (traditional) process algebra. So, for these cases, more research is needed in order to find the best way of integrating the elegance of representing knowledge by indistinguishability relations with the ease of specifying the protocol operationally.

Future Work. First of all, we will build tool support for model checking $E\bar{\mu}$ properties on ALTSs. Ideally, this can be achieved by embedding the new framework in an existing verification tool-set. The starting point will be our already existing Maude prototype [1]. Then we wish to experiment with applying this technique to protocols from the categories mentioned above. On a more theoretical direction, a question is whether it is possible to extend the sequent-based compositional proof system developed for the SOS + Hennessy-Milner Logic [27] in order to cope with $E\bar{\mu}$ formulas, as well. Finally, this framework can support a direct comparison of the operational and epistemic definitions of various properties. For instance, anonymity is defined operationally as (trace) equivalence between certain processes, while epistemically it is simply a negative knowledge formula. The issue of which of these definitions is stronger, if any, is not clear yet and deserves further investigation.

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