

Epistemic Semantics in Guarded String Models

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Abstract

Constructive and computable multi-agent epistemic possible worlds models are defined, where possible worlds models are guarded string models in an epistemic extension of Kleene Algebra with Tests. The account is framed as a formal language Epik (Epistemic KAT) for defining such models. The language is implemented by translation into the finite state calculus, and alternatively by modeling propositions as lazy lists in Haskell. The syntax-semantics interface for a fragment of English is defined by a categorial grammar.

1 Introduction and Related Work

Linguistic semantics in the Montague tradition proceeds by assigning propositional *semantic values* to disambiguated sentences of a natural language. A proposition is a set or class of *possible worlds*. These are often assumed to be things with the same nature and complexity as the world we occupy (Lewis, 1986). But alternatively, one can work with small idealized models, in order to illustrate and test ideas. The point of this paper is to scale up toy or idealized models to countable sets of worlds, and to constructive and computable modeling of epistemic alternatives for agents. We describe a certain systematic way of defining such models, and illustrate how to apply them in natural language semantics. The focus is on epistemic semantics and clausal embedding. The fundamental move is to identify possible worlds with strings of primitive events, so that propositions are sets of strings. An advantage in this is that it allows for a mathematical description of an algebra of propositions, coupled with a computational representation using either lazy lists of strings, or finite state machines that describe sets of strings.

The approach taken here synthesizes five antecedents in a certain way. John McCarthy's *Situation*

Calculus is the source of the idea of constructing possible worlds as event sequences (McCarthy, 1963; Reiter, 2001). The algebraic theory of *Kleene Algebra with Tests* characterizes algebras with elements corresponding to propositions and event types in our application (Kozen, 2001). *Action models* in dynamic epistemic semantics introduce the technique of constructing epistemic models from primitive alternative relations on events, in order to capture the epistemic consequences of perceptual and communicative events (Baltag et al., 1999). Literature on *finite state methods in linguistic semantics* has used event strings and sets of event strings to theorize about tense and aspect in natural language semantics (Fernando, 2004, 2007; Carlson, 2009) and to express intensions (Fernando, 2017). Work on *finite state intensional semantics* has investigated how to do the semantics of intensional complementation in a setting where compositional semantics is expressed in a finite state calculus (Rooth, 2017; Collard, 2018).

A running example of an event-sequence model is *The Concealed Coin*. Amy and Bob are seated at a table. There is a coin on the table under a cup, heads up. The coin could be heads-up *H* or tails-up *T*, and neither agent knows which it is. This initial situation is possible world w_1 . Two additional worlds w_2 and w_3 are defined by sequencing events after the initial state, with events interpreted as in (1). The truth values for English sentences shown in (3) are observed, where 0 stands for falsity and 1 for truth.

- (1) a_1 Amy peeks at *H*, by tipping the cup. Bob sees she's peeking, but not what she sees.
- b_1 Bob peeks at *H*.
- a_0 Amy peeks at *T*.
- b_0 Bob peeks at *T*.
- a_{01} Amy secretly turns the coin from *T* to *H*. She knows she turned the coin over, but

100 not which side was face up. Bob thinks
 101 nothing happened.
 102 a_{10} Amy secretly turns the coin from H to T .
 103 a_{01} Bob secretly turns the coin from T to H .
 104 b_{10} Bob secretly turns the coin from H to T .
 105
 106 (2) $w_2 = w_1 a_1$ $w_3 = w_2 b_1$ $w_4 = w_3 a_{10} b_{01} b_1$
 107 (3) $w_1 \quad w_2 \quad w_3 \quad w_4 \quad$ Sentence
 108 0 1 1 0 Amy knows it's heads.
 109 0 0 1 1 Bob knows it's heads.
 110 0 0 1 0 Bob knows Amy
 111 knows it's heads.
 112 0 1 1 0 Bob knows Amy
 113 knows whether it's
 114 heads or tails.

[ehc]: I'm not sure if these sentences are the
 most interesting anymore!

The events come with pre-conditions and post-conditions. Amy can turn the coin from heads to tails only if the coin is heads-up, so a_{10} has the pre-condition of the coin being heads up. Once she turns the coin over, tails must be face-up, so a_{10} has the post-condition of the coin being tails-up. Let h be the Boolean proposition that the coin is heads up and t be the Boolean proposition that the coin is tails-up. Then pre- and post-conditions can be described by Boolean formulas, with h being the pre-condition of a_{10} and a_{01} being the post-condition. This is expressed using an operator “ $:$ ” (read “and next”) that pairs Boolean formulas. The formula $h : t$ describes a_{10} (Amy turning the coin from heads to tails) as happening only in an h state, and concluding in a not- h state. Events don't have to change state: the event a_0 (Amy peeking at tails) can happen only in a t state, and does not change the state ($t : t$).

However a coin cannot be showing both heads and tails! Currently the precondition h of a_{10} only says that heads must be showing, and says nothing about the fact that tails must be face-down, indicated by the formula \bar{t} . We will further restrict the feasible conditions for our actions by restricting the space of valuations for our formulae.

A sequence such as $\bar{h}t$ can be viewed both as a formula and as a valuation of primitive propositions, which we use to describe world state. The primitives are listed in fixed order, and left unmarked (indicating true) or marked with the overbar (indicating false). Since a coin is heads or tails but not both, we want to allow the valuations $h\bar{t}$ and $\bar{h}t$, and disallow ht and $\bar{h}\bar{t}$. This is enforced by a state

state formulas	$(a \in \mathbf{B})$	150
$\rho, \sigma, \varphi ::= a \mid 0 \mid 1 \mid \rho + \sigma \mid \rho\sigma \mid \bar{\rho}$		151
effect formulas		152
$\zeta, \eta ::= \rho : \sigma \mid \zeta + \eta \mid \zeta \& \eta \mid \bar{\zeta}$		153
$\llbracket \rho : \sigma \rrbracket^\varphi = \mathcal{A}_\mathbf{B}^{\rho\varphi} \times \mathcal{A}_\mathbf{B}^{\sigma\varphi}$		154
$\llbracket \zeta + \eta \rrbracket^\varphi = \llbracket \zeta \rrbracket^\varphi \cup \llbracket \eta \rrbracket^\varphi$		155
$\llbracket \zeta \& \eta \rrbracket^\varphi = \llbracket \zeta \rrbracket^\varphi \cap \llbracket \eta \rrbracket^\varphi$		156
$\llbracket \bar{\zeta} \rrbracket^\varphi = \mathcal{A}_\mathbf{B}^\varphi \times \mathcal{A}_\mathbf{B}^\varphi \setminus \llbracket \zeta \rrbracket^\varphi$		157

Figure 1: Syntax of state formulas and syntax and semantics of effect formulas. Effect formulas denote relations between atoms. In a state formula, juxtaposition $\rho\sigma$ is conjunction.

formula, which is a Boolean formula, in this case the one given on the second line of (4). Where \mathbf{B} is a set of atomic tests and ϕ is a state constraint over \mathbf{B} , $\mathcal{A}_\mathbf{B}^\phi$ is the set of valuations of \mathbf{B} that make formula ϕ true. Valuations are called atoms, because they correspond to the atoms of a Boolean algebra of tests (Kozen, 2001).

Formulas like the ones in (??) that describe pre- and post-conditions are *effect formulas*. They are interpreted as defining relations between atoms, as defined in Figure 1. The atoms they relate are constrained by the state formula as well. For the heads-tails example, let the state formula and the effect formula for a_1 (Amy peeking at heads) be as specified in (4). Then $\mathcal{A}_\mathbf{B}^\varphi$ and the relation on atoms for the event a_1 are as given at the bottom in (4).

(4)	\mathbf{B}	$\{h, t\}$	178
	state formula φ	$h\bar{t} + \bar{h}t$	179
	effect formula ζ for a_1	$h : h$	180
	$\mathcal{A}_\mathbf{B}^\varphi$	$\{h\bar{t}, \bar{h}t\}$	181
	$\llbracket \zeta \rrbracket^\varphi$	$\{\langle h\bar{t}, \bar{h}t \rangle\}$	182

2 Epistemic guarded string models

Epik is a specification language for possible worlds models that includes declarations of events and states, state formulas, effect formulas, and additional information. Figure 2 shows an Epik program that describes a possible worlds model for two agents with information about one coin, and events of the agents semi-privately looking at the coin. The line beginning with state enumerates \mathbf{B} . The line beginning with restrict gives the state formula. The lines beginning with event declare events and their effect formulas. Finally the lines beginning with agent define *event alternative* relations for agents. Each clause with an arrow has a single event symbol on the left, and a

```

200
201 state h t      agent amy
202 restrict h!t    o1 -> o1
203           + t!h  o0 -> o0
204 event o1 h:h   a1 -> a1
205 event o0 t:t   a0 -> a0
206 event a1 h:h   b1 -> b1 + b0
207 event a0 t:t   b0 -> b1 + b0
208 event b1 h:h   a10 -> a10 + a01
209 event b0 t:t   a01 -> a10 + a01
210 event a10 h:t  b10 -> o0 + o1
211 event a01 t:h  b01 -> o0 + o1
212 event b10 h:t
213 event b01 t:h  agent bob
214           <sim. swap a and b>

```

Figure 2: Epik program describing a possible-worlds event sequence model for two agents with information about one coin, and events of the agents semi-privately looking at the coin.

disjunction of alternative events on the right of the arrow. The interpretation of Amy’s alternatives for b_1 (Bob peeks at heads), is that when b_1 happens, for Amy either b_1 or b_0 (Bob peeks at tails) could be happening. Her alternatives for a_{01} and a_{10} (she turns the coin over) are a_{10} and a_{01} , indicating that she doesn’t know, *a priori*, whether she’s turning the coin from H to T or from T to H . Similarly, Bob secretly turns the coin over, in b_{10} or b_{01} , she doesn’t know anything has happened, so her alternatives are the no-operation events o_1 and o_0 for heads-worlds and tails-worlds respectively. Bob’s alternatives are the same, *mutatis mutandi*.

This paper focuses on defining a concrete possible worlds model from an Epik specification. The models are an extension of guarded-string models for Kleene Algebra with Tests (KAT). This is an algebraic theory that has model classes including guarded string models, relational models, finite models, and matrix models. Our definitions and notation follow (Kozen, 2001). We add syntax and semantics is included to cover multi-agent epistemic semantics.

Guarded strings over a finite alphabet P are like ordinary strings, but with atoms over a set B alternating with the symbols from P . In the algebra described by Figure 2, P is the set of events $\{a_1, a_0, b_1, b_0, a_{10}, a_{01}, b_{10}, b_{01}\}$, and B is $\{h, t\}$.

In the coin example, as we already saw in (4), \mathcal{A}_B^φ is $\{ht, \bar{ht}\}$, for which we use the shorthand $\{H, T\}$. A guarded string over P and B is a strings of events from P , alternating with atoms over B , and beginning and ending with atoms. (??) gives the encoding as guarded strings of the worlds in (??) and (1). The length of a guarded string p , written $|p|$ is the number of events in p . An atom such

as H is a guarded string of length 0. Correspondingly $|w_1| = 0$, $|w_2| = 1$ and $|w_3| = 2$.

The discussion of (2) mentioned building worlds by incrementing worlds with events. This is accomplished in guarded string models with fusion product \diamond , a partial operation that combines two guarded strings, subject to the condition that the atom at the end of the the first argument is identical to the atom at the start of the second one. (5) gives some examples.

$$(5) \quad H b_1 H \diamond H a_1 H = H b_1 H a_1 H \\ T b_{01} H \diamond T a_1 T = \text{undefined}$$

Rather than individual guarded strings, elements of a guarded string model for KAT are sets of guarded strings. In our application, these elements have the interpretation of propositions, which are sets of possible worlds. In a free guarded string model for KAT, any event can be adjacent to any atom in a guarded string that is an element of the underlying set for the algebra. We instead impose the constraints coming from the state and effect formulas. (6) defines the well-formed guarded strings determined by and Epik specification. Condition (i) says that each atom is consistent with the state constraint, and condition (ii) says that each constituent token event $\alpha_i e_i \alpha_{i+1}$ is consistent with the effect constraint on e_i .¹

$$(6) \quad \begin{aligned} \text{Given } P, B, \text{ a state formula } \varphi, \text{ and an effect formula } \zeta_e \text{ for each event } e \text{ in } P, \\ \alpha_0 e_0 \dots e_n \alpha_{n+1} \text{ is well-formed iff} \end{aligned}$$

$$\begin{aligned} \text{(i) } \alpha_i \in \mathcal{A}_B^\varphi \text{ } (0 \leq i \leq n), \text{ and} \\ \text{(ii) } \langle \alpha_i, \alpha_{i+1} \rangle \in [\zeta_e]^\varphi, \text{ } (0 \leq i \leq n). \end{aligned}$$

Well-formed guarded strings have the interpretation of worlds in the application to natural-language semantics. The set of possible worlds in the Kripke frame determined by an Epik specification is the set of well-formed guarded strings. At this point, we could say that any set of worlds is a proposition, so that the set of propositions is the power set of the set of worlds (Montague and Thomason, 1975; Callin, 1975). We will instead define a more restrictive set

¹ An alternative is to define equations such as $\bar{\phi} = 0$ (from the state formula ϕ) and $a_1 = ha_1h$ (from the effect formula $h : h$ for event a_1), and construct a quotient algebra from the equivalence relation generated by these equations. This results in equating sets of guarded strings in the free algebra that differ by guarded strings that are ill-formed according to the state and effect formulas. In the development in the text, we instead use a set of guarded strings that are well-formed according to the state and effect formulas as the representative of the equivalence class.

of propositions corresponding to the regular sets of strings. This is deferred to the next section. Certain sets of well-formed guarded strings have the additional interpretation of event types. An event-type is something that can “happen” in different worlds. For example, a_1 has the event type $\{H a_1 H\}$, and a_0 has the even type $\{T a_0 T\}$. The event types for b_0 and b_1 are analogous.

The construction so far defines a set of worlds from an Epik specification. Normally the set is countably infinite, though some choices of effect formulas can result in a finite set of worlds. The next step is to define an alternative relation R_a on worlds for each agent a . This will result in a Kripke frame $\langle W, R_1, \dots, R_n \rangle$ consisting of a set of worlds, and a world-alternative relation for each agent (Kripke, 1963). An Epik specification defines an alternative relation on bare events for each agent a , which we notate as \hat{R}_a . This should be lifted to a relation R_a on worlds. The basic idea is that when a world w is incremented with an event e , in the resulting world $w \diamond e$, epistemic alternatives for agent a are of the form $w' \diamond e'$, where w' is an alternative to w for a in w , and e' is an event-alternative to e for a .² This needs to be implemented in a way that takes account of pre- and post-conditions for events. For this, our approach is to refer the definition of well-formed guarded strings. (7) defines a relation on worlds from a relation on bare events.

- (7) Let W be a set of guarded strings over events P and primitive tests B , and \hat{R} be a relation on P . The corresponding relation R on W holds between a guarded string $\alpha_0 e_0 \dots e_n \alpha_{n+1}$ in W and a guarded string q iff q is an element of W and is of the form $\alpha'_0 e'_0 \dots e'_n \alpha'_{n+1}$, where for $0 \leq n$, $\langle e_i, e'_i \rangle \in \hat{R}$.

This requires that in an alternative world, each constituent event e'_i is an alternative to the event e_i in the base world. Compatibilities between events in the alternative world are enforced by the require-

²In this it is important that the event-alternative relation for an agent is constant across worlds. We anticipate that the definition given here produces results equivalent to what is found in literature on event alternatives in dynamic epistemic semantics, though we have not verified this. That literature primarily focuses on mapping an epistemic model for a single time and situation to another, and uses general first-order models, rather than guarded string models. See Baltag et al. (1999), Van Ditmarsch et al. (2007), and articles in Van Ditmarsch et al. (2015). Previous literature is motivated by epistemic logic and AI planning, rather computable possible worlds models in natural language semantics.

events $e \in P$	350
$p, q ::= e \mid \sigma \mid p + q \mid pq \mid p^* \mid \neg p \mid \diamond_a p$	351
$\square_a p \triangleq \neg \diamond_a \neg p$	352
$p \wedge q \triangleq \neg(\neg p + \neg q)$	353
$p \rightarrow q \triangleq \neg p + q$	354

Figure 3: The language of Epik terms and key derived operators.

ment that the alternative world is an element of W , so that state and effect formulas are enforced.

Consider a scenario like the one from Figure 1, but with an additional agent Cal. The base world $Tb_0 T c_0 T$ is one where the coin is tails, and first Bob looks at tails, and then Cal looks at tails. The first event b_0 has the alternatives b_0 and b_1 for Amy, and the second event c_0 has the alternatives c_0 and c_1 for Amy. This results in four combinations $b_0 c_0$, $b_0 c_1$, $b_1 c_0$, and $b_1 c_1$. But these are filtered by post- and pre-conditions of events in the alternative world, so that the set of alternatives for Amy in $Tb_0 T c_0 T$ is $\{Tb_0 T c_0 T, H b_1 H c_1 H\}$, with two world-alternatives instead of four.

3 The logical language of Epistemic KAT

The standard language for Kleene algebra with tests has the signature $\langle K, +, \cdot, *, \bar{}, 0, 1 \rangle$ (Kozen, 2001). In a guarded string model for KAT, K is a set of sets of guarded strings, $+$ is set union, the operation \cdot is fusion product raised to sets, $*$ is Kleene star, the operation $\bar{}$ is complement for tests, 0 the empty set, and 1 is the set of atoms.³ To this we add a unary modal operation \diamond_a for each agent, and a unary complement operation \neg on elements of K . Intuitively, $\diamond_a p$ is the set of worlds where proposition p is epistemically possible for agent a . Propositional complement is included because natural languages have sentence negation. In addition, universal box modalities are defined as duals of existential diamond modalities.

With modalities and propositional negation added, the signature of n -agent epistemic KAT is $\langle K, +, \cdot, *, \bar{}, 0, 1, \neg, \diamond_1 \dots \diamond_n \rangle$. Figure 3 defines the syntax of the language. Juxtaposition is used for product. Terms in this language are used to represent the propositional semantic values of English sentences. (8) gives some examples. To explain the first one \bullet as defined in Figure 3 is the disjunction of the primitive events. Since a world is a well-formed sequence of events, \bullet^* is the set of worlds.

³0 has the dual role the identity for + (union), and as False for operations on tests. 1 has the dual role of the identity for product (fusion product raised to sets), and True for tests.

Multiplying by the state symbol h in the term $\bullet^* h$ has the effect of conjoining h with the atom at the end of the world. So $\bullet^* h$ is the set of worlds where the coin ends heads-up⁴.

(8)	$\bullet^* t$	It's tails.
	$\bullet^* h$	It's heads.
	$\bullet^* h \wedge \square_a \bullet^* h$	Amy knows it's heads.
	$\square_b (\square_a \bullet^* t + \square_a \neg \bullet^* t)$	Bob believes Amy knows whether it's tails.

[ehc]: I took the ‘that’s out of these sentences. I remember from class that even if they are assigned null in the PF they still exist in the LF. Is it okay to leave it out here?

3.1 Standard Epistemic Modalities

Using our existential modal primitive \diamond_a , and the dual encodings of \square_a and \wedge , we can encode the standard modal operators expressing knowledge (\mathcal{K}_a) and belief (\mathcal{B}_a) into Epik⁵. These encodings are shown below:

$$(9) \quad \begin{array}{ll} \text{BELIEF} & \mathcal{B}_a p \triangleq \square_a p \\ \text{KNOWLEDGE} & \mathcal{K}_a p \triangleq p \wedge \mathcal{B}_a p \end{array}$$

To construct different types of reasoners (e.g. accurate, inaccurate, etc), users of Epik can construct an agents alternative relation accordingly. Observe the discussion of modal axioms **T** and **D** in Section 3.3.

3.2 Guarded String Interpretation

A term p of the logical language is interpreted as a set of guarded strings $\llbracket p \rrbracket^{B,P,\varphi,\zeta}$, where superscript captures dependence on an Epik specification. Figure 4 defines the interpretation. The interpretation $\llbracket 1 \rrbracket^{B,P,\varphi,\zeta}$ of the multiplicative identity 1 is the set of atoms that satisfy the state constraint φ . Where b is a primitive Boolean, $\llbracket b \rrbracket^{B,P,\varphi,\zeta}$ is the set of atoms that satisfy the state constraint and where b is true. Where e is a primitive event, $\llbracket e \rrbracket^{B,P,\varphi,\zeta}$ is the set of guarded strings that have the form of e flanked by compatible atoms, as determined by the event formula ζ_e . The product pq is interpreted with fusion product raised to sets of guarded strings. Kleene star is interpreted as the union of exponents (p^n is

⁴A mapping from English sentences to logical terms in epistemic KAT is presented in Section 6

⁵The choice to refer to \diamond_a as an “epistemic” primitive rather than a “doxastic” primitive, is that it is essential in constructing both the doxastic and epistemic operators. A “doxastic” moniker would suggest the unrepresentability of epistemic modalities

$\llbracket 0 \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \emptyset$	450
$\llbracket 1 \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \mathcal{A}_B^\varphi$	451
$\llbracket b \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \mathcal{A}_B^{b\varphi}$	452
$\llbracket \bar{\sigma} \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \mathcal{A}_B^\varphi \setminus \llbracket \sigma \rrbracket^{B,P,\varphi,\zeta}$	453
$\llbracket e \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \{\alpha e \beta \alpha \zeta_e \beta\}$	454
$\llbracket p+q \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \llbracket p \rrbracket^{B,P,\varphi,\zeta} \cup \llbracket q \rrbracket^{B,P,\varphi,\zeta}$	455
$\llbracket pq \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \left\{ \begin{array}{l l} x \diamond y & x \in \llbracket p \rrbracket^{B,P,\varphi,\zeta} \\ y \in \llbracket q \rrbracket^{B,P,\varphi,\zeta} & \\ \end{array} \right. \begin{array}{l} x \diamond y \text{ is defined} \end{array} \right\}$	456
$\llbracket p^* \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \bigcup_{n \geq 0} \llbracket p^n \rrbracket^{B,P,\varphi,\zeta}$	457
$\llbracket \neg p \rrbracket^{B,P,\varphi,\zeta}$	$\triangleq \llbracket \bullet^* \rrbracket^{B,P,\varphi,\zeta} \setminus \llbracket p \rrbracket^{B,P,\varphi,\zeta}$	458
$\llbracket \diamond_a p \rrbracket$	$\triangleq \{x \exists y. x \hat{R}_a y \wedge y \in \llbracket p \rrbracket^{B,P,\varphi,\zeta}\}$	459

Figure 4: Interpretation of Epik terms as sets of guarded strings

the n -times product of p with itself, with $p^0 = 1$). Propositional complement is complement relative to the set of worlds. The epistemic formula $\diamond_a p$ is interpreted with Kripke semantics for epistemic modality, as the pre-image of the embedded proposition under the world-alternative relation \hat{R}_a .

Summing up, given an Epik specification B, P, φ, ζ , term p (as defined syntactically in Figure 3) is interpreted as a set of guarded strings $\llbracket p \rrbracket^{B,P,\varphi,\zeta}$. Let $K^{B,P,\varphi,\zeta}$ be the sets that are interpretations of terms. Then $\langle K^{B,P,\varphi,\zeta}, +, \cdot, *, \bar{,}, 0, 1, \neg, \diamond_{a_1}, \dots, \diamond_{a_n} \rangle$ is a concrete guarded string interpretation for the signature of epistemic KAT, with operations as in Figure 4 (e.g. the binary operation $+$ is union, and the unary operation \diamond_a is pre-image relative to \hat{R}_a). This provides a concrete n -agent Kripke frame $\langle \llbracket \bullet^* \rrbracket^{B,P,\varphi,\zeta}, \hat{R}_1, \dots, \hat{R}_n \rangle$.⁶ The frame consists of a set of worlds, and an epistemic-alternative relation for each agent. It is used as a target for natural-language interpretation in Section 6.

3.3 Axiomatic Classification

To situate our logic as a modal logic, we investigate the soundness of the standard modal axioms (?) in Epik’s semantics. Some of these standard axioms ((10)) hold all the time, i.e. they are *valid*, and the remaining axioms are valid when \hat{R}_a has a certain shape. The axioms in (11) have a nontrivial condition validity condition.

$$(10) \quad \begin{array}{ll} \mathbf{N} & \text{If } p \text{ is valid, then } \square_a p \text{ is valid} \\ \mathbf{K} & \square_a(p \rightarrow q) \rightarrow \square_a p \rightarrow \square_a q \text{ is valid.} \end{array}$$

⁶The domain of the Kripke frame differs from the domain of the guarded string model, because the former is the set of worlds, while the latter is the set of propositions.

```

500      St
501      Atomic Tests such as 0110.
502      UnequalStPair
503      Sequence of two unequal tests such as 0110 0111.
504      define Wf0 ~[$ UnequalStPair];
505      String that doesn't contain a non-matching test pair.
506      define Squash St -> 0 || St _;
507      Rewrite relation deleting the second of two tests.
508      define Cn(X,Y)
509          [[[X Y] & Wf0] .o. Squash].l;
510          KAT product.
511          define Kp1(X)
512              [[[X+] & Wf0] .o. Squash].l;
513          define Kst(X) St | Kp1(X);
514          KAT Kleene plus and Kleene star. The Fst operation | is
515          union.

```

Figure 5: Definition in Fst of KAT product and star.

$$\begin{aligned}
 (11) \quad \mathbf{T} \quad \square_a p \rightarrow p & \quad \text{if } g \hat{R}_a g, \forall g \\
 \mathbf{D} \quad \square_a p \rightarrow \diamond_a p & \quad \text{if } g \in \text{dom}(\hat{R}_a), \forall g \\
 \mathbf{4} \quad \square_a p \rightarrow \square_a \square_a p & \quad \text{if } \hat{R}_a \text{ idempotent}
 \end{aligned}$$

The condition on **4** is essentially just a restatement of the theorem in relational terms. The conditions on the remaining standard modal axioms, **B** and **5**, are of a similarly trivial flavor.

4 Translation into the finite state calculus

The finite state calculus is an algebra of regular sets of strings and regular relations between strings that was designed for use in computational phonology and morphographemics (Kaplan and Kay, 1994; Beesley and Karttunen, 2003). Current implementations allow for the definition of functions on regular sets and relations (Hulden, 2009; Karttunen, 2010). Such definitions are used here to construct of a model for epistemic KAT inside the finite state calculus. We describe our translation from Epik terms to Fst programs here.

First, the space of worlds is a set of ordinary (as opposed to guarded) strings. Bit sequences (sequences of 0's and 1's) encode atoms, as before, these alternate with event symbols to encode a world. (12) gives the encoding of worlds w_2 and w_3 from the example. The valuation of h preceeds the valuation of t , so 1 0 indicates the valuation ht .

$$\begin{aligned}
 (12) \quad w_2 & \quad 1 \ 0 \ a1 \ 1 \ 0 \\
 w_3 & \quad 1 \ 0 \ a1 \ 1 \ 0 \ b1 \ 1 \ 0
 \end{aligned}$$

Terms in the finite state calculus are interpreted as sets of strings, or for relational terms, as relations between strings. Computationally, the sets and relations are represented by finite state acceptors. As used here, a program in the Fst language of the finite state calculus is a straight-line program

that defines a sequence of constants naming sets, constants naming relations, and functions (defined as macros) mapping one or more regular sets or relations to a regular set or relation.

Now, translating the Epik terms 0, 1, b , and e are straightforward: we simply convert the atoms as previously described, ensuring to decorate the events e with their compatible atoms first. For example a_1 becomes $\{01a_101\}$. Fst also has built-in notions of union ($|$), intersection ($\&$), and complement (\sim). Translating the the remaining operators requires more work.

Implementing fusion product using Fst's standard string concatenation (denoted by juxtaposition XY) requires more care. Naively concatenating strings with atoms (Boolean vectors) at both ends doubles the atoms at the juncture, and does not enforce the requisite atom equality.

To implement the fusion product, we define the binary product operation Cn , which combines strings in the underlying string algebra, remove strings with non-matching atoms, and then delete the second of two tests to create well-formed guarded strings (see Figure 5). The set $Wf0$ describes pairs of equal atoms as the complement of set of unequal atom pairs, implemented using Fst's containment operator $\$$. Then, to delete the second of the two (matching) pairs, the $Squash$ operator uses Fst's rewrite notation to delete atoms (St) that are preceded by another atom.⁷ The squash operator is applied via the relational composition $.o.$ and codomain $.l$ operators.

Kleene star is defined in a similar way (see Figure 5), unioning the set of atoms St with $Kp1$ which uses Fst's non-empty iteration operator $+$ and normalizes the result in the same way as Cn .

It remains to define an epistemic alternative relation on worlds for each agent. The relevant information in Figure 2 is a relation between bare events for each agent. This determines a relation in the guarded string algebra a relation between bare events decorated with compatible tests. For agent Amy, this is the relation described in (13) as a set of ordered pairs.

⁷ This is a non-equal length regular relation. The finite state calculus includes such relations, and they can be used with relation composition and relation domain and co-domain. They are restricted in that the complement and set difference for non-equal length relations is not defined. The epistemic alternative relations that are defined in Figure – are equal-length relations.

```

600 define RelKpl(R)
601   Squash.i . o . Wf0 . o . [R+] . o . Wf0 . o . Squash
602   c   b   a   b   c
603   a Relational Kleene plus in the string algebra
604   b Constrain domain and co-domain to contain
605     no unmatched tests.
606   c Reduce doubled tests to a single
607     test in the domain and co-domain.
608 define RelKst(R) [St . x . St] | Kpl(X);
609   The Fst operation .x. is Cartesian product. R.i is the
610   inverse of relation R.

```

Figure 6: Definition in Fst of the Kleene concatenation closure of a relation between guarded strings.

$$(13) \left\{ \begin{array}{l} \langle 10a_110, 10a_110 \rangle, \langle 01a_001, 01a_001 \rangle, \\ \langle 10b_110, 10b_110 \rangle, \langle 10b_110, 01b_001 \rangle, \\ \langle 01b_001, 10b_110 \rangle, \langle 01b_001, 01b_001 \rangle \end{array} \right\}$$

The relation on decorated events needs to be generalized to a relation of worlds. The principle for this is that an epistemic alternative to a world of the form we is a world of the form vd , where v is a world-alternative to w , d is an event-alternative to e , and vd is defined (i.e. the world alternative v satisfies the pre-conditions of the event alternative d). This principle is found in earlier literature (Moore 198x, Baltag, Moss and Solecki 20xx).

In Fst, we use the Kleene closure of the concatenation product operation on relations to lift a relation on events for an agent a , R_a , to the corresponding relation on worlds. First define the concatenation product $R S$ of two relations R and S to be the set of pairs of the form $\langle x_1x_2, y_1y_2 \rangle$, where $x_1 R y_1$, and $x_2 S y_2$. Then $R+$ is the closure of R with respect to this operation. Figure ?? defines the corresponding operation in the guarded string algebra. The epistemic alternative relation on worlds for an agent is then defined as the concatenation closure of the event alternative relation for the agent.

5 Bounded Lazy Interpretation

We also implement the semantics of Epik terms using lazy lists in Haskell, rather than the direct interpretation as sets. Using lists sidesteps checking the set invariant (elements are unique) for large sets, such as \bullet^* , and laziness allows us to delay computing these large sets until they are actually needed. To sidestep the infiniteness of models, we parameterize the interpretation function on a positive integer n and only produce guarded strings of length n or less.

The bounded interpretation into lists of strings is very similar to the unbounded interpretation into

$(p)_0^{B,P,\phi,\zeta} \triangleq$	$[]$	650
$(0)_n^{B,P,\phi,\zeta} \triangleq$	$[]$	651
$(1)_n^{B,P,\phi,\zeta} \triangleq$	$[A_B^\varphi]$	652
$(e)_n^{B,P,\phi,\zeta} \triangleq$	$[\alpha e \beta \mid \alpha \in e \beta]$	653
$(b)_n^{B,P,\phi,\zeta} \triangleq$	$[A_B^{b\psi}]$	654
$(p+q)_n^{B,P,\phi,\zeta} \triangleq$	$(p)_n^{B,P,\phi,\zeta} ++ (q)_n^{B,P,\phi,\zeta}$	655
$(p;q)_n^{B,P,\phi,\zeta} \triangleq$	$((p)_n^{B,P,\phi,\zeta} \diamond (q)_n^{B,P,\phi,\zeta}) _n$	656
$(p^*)_n^{B,P,\phi,\zeta} \triangleq$	$[] + ((p)_n^{B,P,\phi,\zeta} \diamond (p^*)_n^{B,P,\phi,\zeta}) _n$	657
	where $i = \max\{1, \min\{ g \mid g \in (p)_n^{B,P,\phi,\zeta}\}\}$	658
$(\neg p)_n^{B,P,\phi,\zeta} \triangleq$	$(\bullet^*)_n^{B,P,\phi,\zeta} \setminus (p)_n^{B,P,\phi,\zeta}$	659
$(\Diamond_a p)_n^{B,P,\phi,\zeta} \triangleq$	$[g' \mid g' \hat{R}_a g, \text{ for } g \in (p)_n^{B,P,\phi,\zeta}]$	660

Figure 7: Bounded interpretation using lazy lists

sets of strings, except for the bounds checking. The full details are shown in Figure ???. First note that when $n = 0$, the denotation is empty, denoted $[]$. Terms of the form 0, 1, e , and ψ have the same denotation as before, translated into a list (denoted $[S]$, for a set S). We compute atoms using BBDs, which concisely represent boolean functions (?).

We lift the remaining operators (except Kleene star) to their list equivalents: union becomes list append (written $++$); fusion product is lifted to lists instead of sets, negation is implemented using list difference (\setminus), and the modal operator lifts the alternative relation over lists of strings⁸. The only caveat to these direct interpretations is that we restrict the operators to have size $\leq n$, denoted as $l|_n$ for a list of guarded strings l .

The denotation of p^* uses the fact that p^* and $1 + p; p^*$ are equivalent, and decrements the size threshold on the recursive denotation of p^* by i , where i is the length of the longest (nonzero) string in the denotation of p , making sure to filter out guarded strings that are too long.

6 Syntax-semantics interface

English sentences are mapped to terms in the logical language via a semantically interpreted multimodal categorial grammar, consisting of a lexicon of words, their categorial types, and interpretations in a logical lambda language. The grammar covers basic statives (*it's heads*), *that-* and *whether-* complements of *know*, predicate and sentence negation, and predicate and sentence conjunc-

⁸Figure ?? depicts this using the list comprehension notation, which is analogous to set builder notation, except that it is written using square brackets. Element order is evoked by the keyword `for`, rather than using the unordered `forall`.

ITEM	TYPE	SEMANTICS
Amy	e	R_a
Bob	e	R_b
it	d	d
heads	$d \setminus_D t$	$\lambda x. \bullet^* h$
tails	$d \setminus_D t$	$\lambda x. \bullet^* t$
is	$(d \setminus t) / (d \setminus_D t)$	$\lambda P x. P x$
knows	$(e \setminus t) / Mt$	$\lambda p R. p \vee \Diamond_{Rp}$
believes	$(e \setminus t) / Mt$	$\lambda p R. \Diamond_{Rp} p$
that	$((e \setminus t) / Mt) \setminus (e \setminus t) / t$	$\lambda p m R. \neg(m (\neg p) R)$
whether	$((e \setminus t) / Mt) \setminus (e \setminus t) / t$	$\lambda p m R. \neg(m (\neg p) R) + \neg(m p R)$

Figure 8: Partial categorial grammar lexicon. The first column has a word form, the second column a categorial type, and third column a semantic translation in a logical language that extends the Epik term language with lambda.

tion. Figure 8 gives illustrative lexical entries.⁹¹⁰ The grammar and semantics are optimized for a simple fragment of English concerned with clausal complementation. The agent names *Amy* and *Bob* contribute the epistemic alternative relations for those agents, rather than individuals. The root verb *know* contributes existential modal force. The complementizers *that* and *whether* are the heads of their dominating clauses, and assemble an alternative relation, modal force, and proposition contributed by the complement. These complementizers introduce the dual via two negations, in order to express universal modal force.

Multimodal categories such as \backslash_D and \backslash_M are used to control the derivation. The semantic translations in the third column of Figure 8 use the logical language, incremented with lambda. The body of $\lambda x. \bullet^* h$, which is the semantic lexical entry for *heads*, is a term denoting the set of all worlds where the coin is heads, expressed as the set of all guarded strings that end with a Boolean valuation where the primitive proposition h (it's heads) is true. The body of $\lambda p. \lambda R. \diamond_{RP}$, which is the semantic lexical entry of *knows*, is a term denoting the pre-image of the world-alternative relation contributed by the subject. This is not the right semantics for *Amy knows that it's heads*, because it is an existential modality \diamond_{RP} , rather than an universal modality \Box_{RP} . This is corrected by the complementizer *that* or *whether*, which introduces the dual.

Sentences are parsed with a chart parser for

⁹Category symbols use Lambek/Bar-Hillel notation for slashes, so that $(d \backslash t) / (d \backslash D t)$ combines with $d \backslash D t$ on the right to give a value that combines with d on the left to give t .

¹⁰Lambda abstractions with multiple parameters are written $\lambda x y. e$ rather than the more verbose $\lambda x. \lambda y. e$.

categorial grammar. The semantics for complex phrases are obtained by application of semantic translations, accompanied by beta reductions that eliminate all lambdas in logical forms for clauses. In consequence, the semantic term translating a sentence is an Epik term. Such a term designates a set of possible words (guarded strings). By way of example, (14a) is an English sentence with conjunction and several levels of clausal embedding. Using the grammar and parser, the sentence is mapped to the term in (14b). Then (14c) shows a simplified logical from constructed form (14b) using simply logical equivalences. This term is compiled in an implementation of the finite state calculus to a finite state machine with six states and eight arcs, which accepts a countably infinite set of worlds. [ehc]: *Is this right anymore? the formula has changed drastically.* In this way the methodology “directly” represents the set of worlds denoted by (14a).

- 14) a. It's tails and Amy knows that Bob knows that Amy knows whether it's heads.

b. $\bullet^*t \wedge \neg(\neg(\neg(\neg(\neg(\neg\bullet^*h \vee \diamond_a \neg\bullet^*h) + \neg(\bullet^*h \wedge \diamond_a \bullet^*h)) + \diamond_b \neg(\neg(\neg\bullet^*h \vee \diamond_a \neg\bullet^*h) + \neg(\bullet^*h \wedge \diamond_a \bullet^*h)))) + \diamond_a \neg(\neg(\neg(\neg(\neg\bullet^*h \vee \diamond_a \neg\bullet^*h) + \neg(\bullet^*h \wedge \diamond_a \bullet^*h)) + \diamond_b \neg(\neg(\neg\bullet^*h \vee \diamond_a \neg\bullet^*h) + \neg(\bullet^*h \wedge \diamond_a \bullet^*h))))$

c. $\bullet^*t \wedge \mathcal{K}_a(\mathcal{K}_b(\mathcal{K}_a \bullet^*h + \mathcal{K}_a \neg\bullet^*h))$

d. Amy knows that it's tails.

e. $\bullet^*t \wedge \neg\diamond_a \neg\bullet^*t \quad (\equiv \mathcal{K}_a \bullet^*t)$

Sentence (14d) is assigned the logical form (14e) by the grammar. Logical relations between propositions are checked in the finite state calculus by checking set-theoretic relations between sets of worlds. In this case, the propositions (14b) and (14e) are equivalent, in the sense that they denote the same set of worlds. This equivalence is attested computationally in the possible worlds model.

7 Discussion

The methodology presented here is designed for use in research in linguistic semantics, and for education at the level of a second graduate course in formal semantics, covering intensionality. There are straightforward extensions to additional semantic phenomena, such as tense and perfective aspect as in (15a), and the combination of metaphysical modality and prospective aspect in (15b).

- (15) a. Amy has learned that Bob had learned
that it's heads.

800 b. Amy might learn that it's heads.
 801

802 The development here was concerned with defining
 803 concrete possible worlds models, and applying
 804 them in natural language semantics. An issue
 805 for further investigation are the mathematical
 806 characterizations of epistemic KATs, e.g. sound and
 807 complete axioms, coalgebra, decidability.

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