Reasoning About Knowledge of Unawareness Revisited

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Abstract

In earlier work [Halpern and Rêgo 2006b], we proposed a logic that extends the Logic of General Awareness of Fagin and Halpern [1988] by allowing quantification over primitive propositions. This makes it possible to express the fact that an agent knows that there are some facts of which he is unaware. In that logic, it is not possible to model an agent who is uncertain about whether he is aware of all formulas. To overcome this problem, we keep the syntax of the earlier paper, but allow models where, with each world, a possibly different language is associated. We provide a sound and complete axiomatization for this logic and show that, under natural assumptions, the quantifier-free fragment of the logic is characterized by exactly the same axioms as the logic of Heifetz, Meier, and Schipper [2008].

1 INTRODUCTION

Adding awareness to standard models of epistemic logic has been shown to be useful in describing many situations (see [Fagin and Halpern 1988; Heifetz, Meier, and Schipper 2006] for some examples). One of the best-known models of awareness is due to Fagin and Halpern [1988] (FH from now on). They add an awareness operator to the language, and associate with each world in a standard possible-worlds model of knowledge a set of formulas that each agent is aware of. They then say that an agent *explicitly knows* a formula φ if φ is true in all worlds that the agent considers possible (the traditional definition of knowledge, going back to Hintikka [1962]) and the agent is aware of φ.

In the economics literature, going back to the work of Modica and Rustichini [1994, 1999] (MR from now on), a somewhat different approach is taken. A possibly different set $\mathcal{L}(s)$ of primitive propositions is associated with each world s. Intuitively, at world s, the agent is aware only of formulas that use the primitive propositions in $\mathcal{L}(s)$. A definition of knowledge is given in this framework, and the agent is said to be aware of φ if, by definition, $K_i\varphi \vee K_i\neg K_i\varphi$ holds. Heifetz, Meier, and Schipper [2006, 2008] (HMS from now on), extend the ideas of MR to a multiagent setting. This extension is nontrivial, requiring lattices of state spaces, with projection functions between them. As we showed in earlier work [Halpern 2001; Halpern and Rêgo 2008], the work of MR and HMS can be seen as a special case of the FH approach, where two assumptions are made on awareness: awareness is *generated by primitive propositions*, that is, an agent is aware of a formula iff he is aware of all primitive propositions occurring in it, and agents know what they are aware of (so that they are aware of the same formulas in all worlds that they consider possible).

As we pointed out in [Halpern and Rêgo 2006b] (referred to as HR from now on), if awareness is generated by primitive propositions, then it is impossible for an agent to (explicitly) know that he is unaware of a specific fact. Nevertheless, an agent may well be aware that there are relevant facts that he is unaware of. For example, primary-care physicians know that specialists are aware of things that could improve a patient's treatment that they are not aware of; investors know that investment fund companies may be aware of issues involving the financial market that could result in higher profits that they are not aware of. It thus becomes of interest to model knowledge of lack of awareness. HR does this by extending the syntax of the FH approach to allow quantification, making it possible to say that an agent knows that there exists a formula of which the agent is unaware. A complete axiomatization is provided for the resulting logic. Unfortunately, the logic has a significant problem if we assume the standard properties of knowledge and awareness: it is impossible for an agent to be uncertain about whether he is aware of all formulas.

In this paper, we deal with this problem by considering the same language as in HR (so that we can express the fact that an agent knows that he is not aware of all formulas, using quantification), but using the idea of MR that there is a different language associated with each world. As we show, this slight change makes it possible for an agent to be uncertain about whether he is aware of all formulas, while still being aware of exactly the same formulas in all worlds he considers possible. We provide a natural complete axiomatization for the resulting logic. Interestingly, knowledge in this logic acts much like explicit knowledge in the original FH framework, if we take "awareness of φ" to mean $K_i(\varphi \vee \neg\varphi)$; intuitively, this is true if all the primitive propositions in φ are part of the language at all worlds that i considers possible. Under minimal assumptions, $K_i(\varphi \vee \neg\varphi)$ is shown to be equivalent to $K_i\varphi \vee K_i\neg K_i\varphi$: in fact, the quantifier-free fragment of the logic that just uses the K_i operator is shown to be characterized by exactly the same axioms as the HMS approach, and awareness can be defined the same way. Thus, we can capture the essence of MR and HMS approach using simple semantics and being able to reason about knowledge of lack of awareness.

Board and Chung [2009] independently pointed out the problem of the HR model and proposed the solution of allowing different languages at different worlds. They also consider a model of awareness with quantification, but they use first-order modal logic, so their quantification is over domain elements. Moreover, they take awareness with respect to domain elements, not formulas; that is, agents are (un)aware of objects (i.e., domain elements), not formulas. They also allow different domains at different worlds; more precisely, they allow an agent to have a subjective view of what the set of objects is at each world. Sillari [2008] uses much the same approach as Board and Chung [2009]. That is, he has a first-order logic of awareness, where the quantification and awareness is with respect to domain elements, and also allows from different subjective domains at each world.

The rest of the paper is organized as follows. In Section 2, we review the HR model of knowledge of unawareness. In Section 3, we present our new logic and axiomatize it in Section 4. In Section 5, we compare our logic with that of HMS and discuss awareness more generally. All proofs are left to the the appendix.

2 THE HR MODEL

In this section, we briefly review the relevant results of [Halpern and Rêgo 2006b]. The syntax of the logic is as follows: given a set $\{1, \ldots, n\}$ of agents, formulas are formed by starting with a countable set $\Phi = \{p, q, \ldots\}$ of primitive propositions and a countable set $\mathcal{X}$ of variables, and then closing off under conjunction ($\wedge$), negation ($\neg$), the modal operators K_i, A_i, X_i, $i = 1, \ldots, n$. We also allow for quantification over variables, so that if φ is a formula, then so is $\forall x\varphi$. Let $\mathcal{L}_n^{\forall,K,X,A}(\Phi, \mathcal{X})$ denote this language and let $\mathcal{L}_n^{K,X,A}(\Phi)$ be the subset of formulas that do not mention quantification or variables. As usual, we define $\varphi \vee \psi$, $\varphi \Rightarrow \psi$, and $\exists x\varphi$ as abbreviations of $\neg(\neg\varphi \wedge \neg\psi)$, $\neg\varphi \vee \psi$, and $\neg\forall x\neg\varphi$, respectively. The intended interpretation of $A_i\varphi$ is "i is aware of φ".

Essentially as in first-order logic, we can define inductively what it means for a variable x to be *free* in a formula φ. Intuitively, an occurrence of a variable is free in a formula if it is not bound by a quantifier. A formula that contains no free variables is called a *sentence*. We are ultimately interested in sentences. If ψ is a formula, let $\varphi[x/\psi]$ denote the formula that results by replacing all free occurrences of the variable x in φ by ψ. (If there is no free occurrence of x in φ, then $\varphi[x/\psi] = \varphi$.) In quantified modal logic, the quantifiers are typically taken to range over propositions (intuitively, sets of worlds), but this does not work in our setting because awareness is syntactic; when we write, for example, $\forall x A_i x$, we essentially mean that $A_i\varphi$ holds for all *formulas* φ. However, there is another subtlety. If we define $\forall x\varphi$ to be true if $\varphi[x/\psi]$ is true for *all* formulas ψ, then there are problems giving semantics to a formula such as $\varphi = \forall x(x)$, since $\varphi[x/\varphi] = \varphi$. We avoid these difficulties by taking the quantification to be over quantifier-free sentences. (See [Halpern and Rêgo 2006b] for further discussion.)

We give semantics to sentences in $\mathcal{L}_n^{\forall,K,X,A}(\Phi, \mathcal{X})$ in awareness structures. A tuple $M = (S, \pi, \mathcal{K}_1, \ldots, \mathcal{K}_n, \mathcal{A}_1, \ldots, \mathcal{A}_n)$ is an *awareness structure for n agents (over Φ)* if S is a set of worlds, $\pi : S \times \Phi \rightarrow \{\mathbf{true}, \mathbf{false}\}$ is an interpretation that determines which primitive propositions are true at each world, $\mathcal{K}_i$ is a binary relation on S for each agent $i = 1, \ldots, n$, and $\mathcal{A}_i$ is a function associating a set of sentences with each world in S, for $i = 1, ..., n$. Intuitively, if $(s, t) \in \mathcal{K}_i$, then agent i considers world t possible at world s, while $\mathcal{A}_i(s)$ is the set of sentences that agent i is aware of at world s. We are often interested in awareness structures where the $\mathcal{K}_i$ relations satisfy some properties of interest, such as reflexivity, transitivity, or the *Euclidean* property (if $(s, t), (s, u) \in \mathcal{K}_i$, then $(t, u) \in \mathcal{K}_i$). It is well known that these properties of the relation correspond to properties of knowledge of interest (see Theorem 2.1 and the following discussion). We often abuse notation and define $\mathcal{K}_i(s) = \{t : (s,t) \in \mathcal{K}_i\}$, thus writing $t \in \mathcal{K}_i(s)$ rather than $(s,t) \in \mathcal{K}_i$. This notation allows us to view a binary relation $\mathcal{K}_i$ on S as a *possibility correspondence*, that is, a function from S to 2^S. (The use of possibility correspondences is more standard in the economics literature than binary relations, but they are clearly essentially equivalent.)

Semantics is given to sentences in $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ by induction on the number of quantifiers, with a subinduction on the length of the sentence. Truth for primitive propositions, for $\neg$, and for $\wedge$ is defined in the usual way. The other cases are defined as follows:[1]

$(M,s) \models K_i\varphi$ if $(M,t) \models \varphi$ for all $t \in \mathcal{K}_i(s)$
$(M,s) \models A_i\varphi$ if $\varphi \in \mathcal{A}_i(s)$
$(M,s) \models X_i\varphi$ if $(M,s) \models A_i\varphi$ and $(M,s) \models K_i\varphi$
$(M,s) \models \forall x\varphi$ if $(M,s) \models \varphi[x/\psi], \forall\psi \in \mathcal{L}_n^{K,X,A}(\Phi)$.

There are two standard restrictions on agents' awareness that capture the assumptions typically made in the game-theoretic literature [Modica and Rustichini 1999; Heifetz, Meier, and Schipper 2006; Heifetz, Meier, and Schipper 2008]. We describe these here in terms of the awareness function, and then characterize them axiomatically.

- Awareness is *generated by primitive propositions (agpp)* if, for all agents i, $\varphi \in \mathcal{A}_i(s)$ iff all the primitive propositions that appear in φ are in $\mathcal{A}_i(s) \cap \Phi$.
- *Agents know what they are aware of (ka)* if, for all agents i and all worlds s,t such that $(s,t) \in \mathcal{K}_i$ we have that $\mathcal{A}_i(s) = \mathcal{A}_i(t)$.

For ease of exposition, we restrict in this paper to structures that satisfy *agpp* and *ka*. If C is a (possibly empty) subset of $\{r,t,e\}$, then $\mathcal{M}_n^C(\Phi,\mathcal{X})$ is the set of all awareness structures such that awareness satisfies *agpp* and *ka* and the possibility correspondence is reflexive (r), transitive (t), and Euclidean (e) if these properties are in C.

A sentence $\varphi \in \mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ is said to be *valid* in awareness structure M, written $M \models \varphi$, if $(M,s) \not\models \neg\varphi$ for all $s \in S$. (This notion is called *weak validity* in [Halpern and Rêgo 2008]. For the semantics we are considering here, weak validity is equivalent to the standard notion of validity, where a formula is valid in an awareness structure if it is true at all worlds in that structure. However, in the next section, we modify the semantics to allow some formulas to be undefined at some worlds; with this change, the two notions do not coincide. As we use weak validity in the next section, we use the same definition here for the sake of uniformity.) A sentence is valid in a class $\mathcal{M}$ of awareness structures, written $\mathcal{M} \models \varphi$, if it is valid for all awareness structures in $\mathcal{M}$, that is, if $M \models \varphi$ for all $M \in \mathcal{M}$.

In [Halpern and Rêgo 2006b], we gave sound and complete axiomatizations for both the language $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ and the language $\mathcal{L}_n^{\forall,X,A}(\Phi,\mathcal{X})$, which does not mention the implicit knowledge operator K_i (and the quantification is thus only over sentences in $\mathcal{L}_n^{X,A}(\Phi)$). The latter language is arguably more natural (since agents do not have access to the implicit knowledge modeled by K_i), but some issues become clearer when considering both. We start by describing axioms for the language $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$, and then describe how they are modified to deal with $\mathcal{L}_n^{\forall,X,A}(\Phi,\mathcal{X})$. Given a formula φ, let $\Phi(\varphi)$ be the set of primitive propositions in Φ that occur in φ.

Prop. All substitution instances of valid formulas of propositional logic.

AGPP. $A_i\varphi \Leftrightarrow \wedge_{p\in\Phi(\varphi)} A_i p$.[2]

KA. $A_i\varphi \Rightarrow K_i A_i\varphi$

NKA. $\neg A_i\varphi \Rightarrow K_i\neg A_i\varphi$

K. $(K_i\varphi \wedge K_i(\varphi \Rightarrow \psi)) \Rightarrow K_i\psi$.

T. $K_i\varphi \Rightarrow \varphi$.

4. $K_i\varphi \Rightarrow K_iK_i\varphi$.

5. $\neg K_i\varphi \Rightarrow K_i\neg K_i\varphi$.

A0. $X_i\varphi \Leftrightarrow K_i\varphi \wedge A_i\varphi$.

$1_\forall$. $\forall x\varphi \Rightarrow \varphi[x/\psi]$ if ψ is a quantifier-free sentence.

$K_\forall$. $\forall x(\varphi \Rightarrow \psi) \Rightarrow (\forall x\varphi \Rightarrow \forall x\psi)$.

$N_\forall$. $\varphi \Rightarrow \forall x\varphi$ if x is not free in φ.

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[1] HR gives semantics to arbitrary formulas, including formulas with free variables. This requires using *valuations* that give meaning to free variables. By restricting to sentences, which is all we are ultimately interested in, we are able to dispense with valuations here, and thus simplify the presentation of the semantics.

[2] As usual, the empty conjunction is taken to be the vacuously true formula *true*, so that $A_i\varphi$ is vacuously true if no primitive propositions occur in φ. We remark that in the conference version of HR, an apparently weaker version of AGPP called *weak generation of awareness by primitive propositions* is used. However, this is shown in HR to be equivalent to AGPP if the agent is aware of at least one primitive proposition, so AGPP is used in the final version of HR, and we use it here as well.

Barcan. $\forall x K_i \varphi \Rightarrow K_i \forall x \varphi$.

MP. From φ and $\varphi \Rightarrow \psi$ infer ψ (modus ponens).

Gen$_K$. From φ infer $K_i\varphi$.

Gen$_\forall$. If q is a primitive proposition, then from φ infer $\forall x \varphi[q/x]$.

Axioms Prop, K, T, 4, 5 and inference rules MP and Gen$_K$ are standard in epistemic logics. A0 captures the relationship between explicit knowledge, implicit knowledge and awareness. Axioms 1$_\forall$, K$_\forall$, N$_\forall$ and inference rules Gen$_\forall$ are standard for propositional quantification.[3] The Barcan axiom, which is well-known in first-order modal logic, captures the relationship between quantification and K_i. Axioms AGPP, KA, and NKA capture the properties of awareness being generated by primitive propositions and agents knowing which formulas they are aware of. Let $\mathrm{AX}^{\mathrm{K,X,A},\forall}$ be the axiom system consisting of all the axioms and inference rules in {Prop, AGPP, KA, NKA, K, A0, 1$_\forall$, K$_\forall$, N$_\forall$, Barcan, MP, Gen$_K$, Gen$_\forall$}.

The language $\mathcal{L}_n^{\forall,X,A}$ without the modal operators K_i has an axiomatization that is similar in spirit. Let K$_X$, T$_X$, 4$_X$, XA, and Barcan$_X$ be the axioms that result by replacing the K_i in K, T, 4, KA, and Barcan, respectively, by X_i. Let 5$_X$ and Gen$_X$ be the axioms that result from adding awareness to 5 and Gen$_K$:

5$_X$. $(\neg X_i\varphi \wedge A_i\varphi) \Rightarrow X_i \neg X_i \varphi$.

Gen$_X$. From φ infer $A_i\varphi \Rightarrow X_i\varphi$.

The analogue of axiom NKA written in terms of X_i, $\neg A_i\varphi \Rightarrow X_i\neg A_i\varphi$, is not valid. To get completeness in models where agents know what they are aware of, we need the following axiom, which can be viewed as a weakening of NKA:

FA$_X$. $\neg\forall x A_i x \Rightarrow X_i \neg \forall x A_i x$.

Finally, consider the following axiom that captures the relation between explicit knowledge and awareness:

A0$_X$. $X_i\varphi \Rightarrow A_i\varphi$.

Let $\mathrm{AX}^{\mathrm{X,A},\forall}$ be the axiom system consisting of all the the axioms and inference rules in {Prop, AGPP, XA, FA$_X$, K$_X$, A0$_X$, 1$_\forall$, K$_\forall$, N$_\forall$, Barcan$_X$, MP, Gen$_X$, Gen$_\forall$}. The following result shows that the semantic properties r, t, e are captured by the axioms T, 4, and 5, respectively in the language $\mathcal{L}_n^{\forall,K,X,A}$; similarly, these same properties are captured by T$_X$, 4$_X$, and 5$_X$ in the language $\mathcal{L}_n^{\forall,X,A}$.

Theorem 2.1: [Halpern and Rêgo 2006b] *If $\mathcal{C}$ (resp., $\mathcal{C}_X$) is a (possibly empty) subset of* $\{\mathrm{T}, 4, 5\}$ *(resp.,* $\{\mathrm{T_X}, 4_\mathrm{X}, 5_\mathrm{X}\}$*) and if C is the corresponding subset of* $\{r,t,e\}$ *then* $\mathrm{AX}^{\mathrm{K,X,A},\forall} \cup \mathcal{C}$ *(resp.,* $\mathrm{AX}^{\mathrm{X,A},\forall} \cup \mathcal{C}_\mathrm{X}$*) is a sound and complete axiomatization of the sentences in* $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ *(resp.* $\mathcal{L}_n^{\forall,X,A}(\Phi,\mathcal{X})$*) with respect to* $\mathcal{M}_n^C(\Phi,\mathcal{X})$.

Consider the formula $\psi = \neg X_i \neg \forall x A_i x \wedge \neg X_i \forall x A_i x$. The formula ψ says that agent i considers it possible that she is aware of all formulas and also considers it possible that she is not aware of all formulas. It is not hard to show ψ is not satisfiable in any structure in $\mathcal{M}(\Phi,\mathcal{X})$, so $\neg\psi$ is valid in awareness structures in $\mathcal{M}(\Phi,\mathcal{X})$, It seems reasonable that an agent can be uncertain about whether there are formulas he is unaware of. In the next section, we show that a slight modification of the HR approach using ideas of MR, allows this, while still maintaining the desirable properties of the HR approach.

3 THE NEW MODEL

We keep the syntax of Section 2, but, following MR, we allow different languages to be associated with different worlds. Define an *extended awareness structure for n agents (over Φ)* to be a tuple $M = (S, \mathcal{L}, \pi, \mathcal{K}_1, \ldots, \mathcal{K}_n, \mathcal{A}_1, \ldots, \mathcal{A}_n)$, where $M = (S, \pi, \mathcal{K}_1, \ldots, \mathcal{K}_n, \mathcal{A}_1, \ldots, \mathcal{A}_n)$ is an awareness structure and $\mathcal{L}$ maps worlds in S to nonempty subsets of Φ. Intuitively, $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s),\mathcal{X})$ is the language associated with world s. We require that $\mathcal{A}_i(s) \subseteq \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s),\mathcal{X})$, so that an agent can be aware only of sentences that are in the language of the current world. We still want to require that *agpp* and *ka*; this means that if $(s,t) \in \mathcal{K}_i$, then $\mathcal{A}_i(s) \subseteq \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(t),\mathcal{X})$. But $\mathcal{L}(t)$ may well include primitive propositions that the agent is not aware of at s. It may at first seem strange that an agent considers possible a world whose language includes formulas of which he is not aware. (Note that, in general, this happens in the HR approach too, even though there we require that $\mathcal{L}(s) = \mathcal{L}(t)$.) But, in the context of knowledge of lack awareness, there is an easy explanation for this: the fact that $\mathcal{A}_i(s)$ is a strict subset of the sentences in $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(t),\mathcal{X})$ is just our way of modeling that the agent considers it possible that there are formulas of which he is unaware; he can even "name" or "label" these formulas, although he may not understand what the names re-

[3] Since we gave semantics not just to sentences, but also to formulas with free variables in [Halpern and Rêgo 2006b], we were able to use a simpler version of Gen$_\forall$ that applies to arbitrary formulas: from φ infer $\forall x\varphi$. Note that all the other axioms and inference rules apply without change to formulas as well as sentences.

fer to. If the agent considers possible a world t where $\mathcal{A}_i(s)$ consists of every sentence in $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(t),\mathcal{X})$, then the agent considers it possible that he is aware of all formulas. The formula ψ in Section 2 is satisfied at a world s where agent i considers possible a world t_1 such that $\mathcal{A}_i(s)$ consists of all sentences in $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(t_1),\mathcal{X})$ and a world t_2 such that $\mathcal{A}_i(s)$ does not contain some sentence in $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(t_2),\mathcal{X})$. Note that we can also describe worlds where agent 1 considers it possible that agents 2 and 3 are aware of the same formulas, although both are aware of formulas that he (1) is not aware of, and other more complicated relationships between the awareness of agents. See Section 5 for further discussion of awareness of unawareness in this setting.

The truth relation is defined for formulas in $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ just as in Section 2, except that for a formula φ to be true at a world s, we also require that $\varphi \in \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s),\mathcal{X})$, so we just add this condition everywhere. Thus, for example,

- $(M,s) \models p$ if $p \in \mathcal{L}(s)$ and $\pi(s,p) = \mathbf{true}$;
- $(M,s) \models \neg\varphi$ if $\varphi \in \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s),\mathcal{X})$ and $(M,s) \not\models \varphi$.
- $(M,s) \models \forall x\varphi$ if $\varphi \in \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s),\mathcal{X})$ and $(M,s) \models \varphi[x/\psi]$ for all $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$.

We leave it to the reader to make the obvious changes to the remaining clauses.

If C be a (possibly empty) subset of $\{r,t,e\}$, $\mathcal{N}_n^C(\Phi,\mathcal{X})$ be the set of all extended awareness structures such that awareness satisfies *agpp* and *ka* and the possibility correspondence is reflexive, transitive, and Euclidean if these properties are in C. We say that a formula φ is *valid in a class $\mathcal{N}$ of extended awareness structures* if, for all extended awareness structures $M \in \mathcal{N}$ and worlds s such that $\Phi(\varphi) \subseteq \mathcal{L}(s)$, $(M,s) \models \varphi$. (This is essentially the notion of weak validity defined in [Halpern and Rêgo 2008].)

4 AXIOMATIZATION

In this section, we provide a sound and complete axiomatization of the logics described in the previous section. It turns out to be easier to start with the language $\mathcal{L}_n^{\forall,X,A}(\Phi,\mathcal{X})$. All the axioms and inference rules of $\mathrm{AX}^{\mathrm{X,A},\forall}$ continue to be sound in extended awareness structures, except for Barcan_X and FA_X. In a world s where $\mathcal{L}(s) = p$ and agent 1 is aware of p, it is easy to see that $\forall x X_i A_i x$ holds. But if agent 1 considers possible a world t such that $\mathcal{L}(t) = \{p,q\}$, it is easy to see that $X_i \forall x A_i x$ does not hold at s. Similarly, if in world t, agent 1 considers s possible, then $\neg\forall x A_i x$ holds at t, but $X_i \neg\forall x A_i x$ does not. Thus, Barcan_X does not hold at s, and FA_X does not hold at t. We instead use the following variants of Barcan_X and FA_X, which are sound in this framework:

Barcan^*_X. $(A_i(\forall x\varphi) \wedge \forall x(A_i x \Rightarrow X_i\varphi)) \Rightarrow X_i(\forall x A_i x \Rightarrow \forall x\varphi)$.

FA^*_X. $\forall x \neg A_i x \Rightarrow X_i \forall x \neg A_i x$.

Let $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$ be the result of replacing FA_X and Barcan_X in $\mathrm{AX}^{\mathrm{X,A},\forall}$ by FA^*_X and Barcan^*_X (the e here stands for "extended").

Theorem 4.1: *If $\mathcal{C}_X$ is a (possibly empty) subset of $\{\mathrm{T_X}, 4_\mathrm{X}, 5_\mathrm{X}\}$ and C is the corresponding subset of $\{r,t,e\}$, then $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall} \cup \mathcal{C}_\mathrm{X}$ is a sound and complete axiomatization of the language $\mathcal{L}_n^{\forall,X,A}(\Phi,\mathcal{X})$ with respect to $\mathcal{N}_n^C(\Phi,\mathcal{X})$.*

The completeness proof is similar in spirit to that of HR, with some additional complications arising from the interaction between quantification and the fact that different languages are associated with different worlds. What is surprisingly difficult in this case is soundness, specifically, for MP. For suppose that M is a structure in $\mathcal{N}_n(\Phi,\mathcal{X})$ such that neither $\neg\varphi$ nor $\neg(\varphi \Rightarrow \psi)$ are true at any world in M. We want to show that $\neg\psi$ is not true at any world in M. This is easy to show if $\Phi(\psi) \subset \Phi(\varphi)$. For if s is a world such that $\Phi(\psi) \subseteq \mathcal{L}(s)$, it must be the case that both φ and $\varphi \Rightarrow \psi$ are true at s, and hence so is ψ. However, if φ has some primitive propositions that are not in ψ, it is a priori possible that $\neg\psi$ holds at a world where neither φ nor $\varphi \Rightarrow \psi$ is defined. Indeed, this can happen if Φ is finite. For example, if $\Phi = \{p,q\}$, then it is easy to construct a structure $M \in \mathcal{N}_n(\Phi,X)$ where both $A_i p \wedge A_i q$ and $(A_i p \wedge A_i q) \Rightarrow \forall x A_i x$ are never false, but $\forall x A_i x$ is false at some world in M. As we show, this cannot happen if Φ is infinite. This in turn involves proving a general substitution property: if φ is valid and ψ is a quantifier-free sentence, then $\varphi[q/\psi]$ is valid. (We remark that the substitution property also fails if Φ is finite.) See the appendix for details.

Using different languages has a greater impact on the axioms for K_i than it does for X_i. For example, as we would expect, Barcan does not hold, for essentially the same reason that Barcan_X does not hold. More interestingly, NKA, 5, and Gen_K do not hold either. For example, if $\neg K_i p$ is true at a world s because $p \notin \mathcal{L}(t)$ for some world t that i considers possible at s, then $K_i \neg K_i p$ will not hold at s, even if the $\mathcal{K}_i$ relation is an equivalence relation. Indeed, the properties of K_i in this framework become quite close to the properties of the explicit knowledge operator X_i in the original FH framework, provided we define the appropriate variant of awareness.

Let $A_i^*(\varphi)$ be an abbreviation for the formula $K_i(\varphi \vee \neg\varphi)$. Intuitively, the formula $A_i^*(\varphi)$ captures the property that φ is defined at all worlds considered possible by agent i. Let AGPP*, XA*, A0*, 5*, Barcan*, FA*, and Gen* be the result of replacing X_i by K_i and A_i by A_i^* in AGPP, XA, A0$_X$, 5$_X$, Barcan$^*_X$, FA$^*_X$, and Gen$_X$, respectively. It is easy to see that AGPP*, A0*, and Gen* are valid in extended awareness structures; XA*, 5*, Barcan*, and FA* are not. For example, suppose that p is defined in all worlds that agent i considers possible at s, so that A_i^*p holds at s. If there is some world t that agent i considers possible at s and a world u that agent i considers possible at t where p is not defined, then A_i^*p does not hold at t, so $K_iA_i^*p$ does not hold at s. It is easy to show that XA* holds if the $\mathcal{K}_i$ relation is transitive. Similar arguments show that 5*, Barcan*, and FA* do not hold in general, but are valid if $\mathcal{K}_i$ is Euclidean and (in the case of Barcan* and FA*) reflexive. We summarize these observations in the following proposition:

Proposition 4.2:

(a) XA* is valid in $\mathcal{N}_n^t(\Phi,\mathcal{X})$.

(b) Barcan* is valid in $\mathcal{N}_n^{r,e}(\Phi,\mathcal{X})$.

(c) FA* is valid in $\mathcal{N}_n^{r,e}(\Phi,\mathcal{X})$.

(d) 5* is valid in $\mathcal{N}_n^{e}(\Phi,\mathcal{X})$.

In light of Proposition 4.2, for ease of exposition, we restrict attention for the rest of this section to structures in $\mathcal{N}_n^{r,t,e}(\Phi,\mathcal{X})$. Assuming that the possibility relation is an equivalence relation is standard when modeling knowledge in any case. Let $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,X,A,A^*,\forall}}$ be the result of replacing Gen$_K$ and Barcan in $\mathrm{AX}^{\mathrm{K,X,A,\forall}}$ by Gen* and Barcan*, respectively, and adding the axioms AGPP*, A0*, and FA* for reasoning about A_i^*. (We do not need the axiom XA*; it follows from 4 in transitive structures.) Let $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*,\forall}}$ consist of the axioms in $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,X,A,A^*,\forall}}$ except for those that mention X_i or A_i; that is, $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*,\forall}} = \mathrm{AX}_{\mathrm{e}}^{\mathrm{K,X,A,A^*,\forall}} - \{$AGPP, KA, NKA, A0$\}$. Note that $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*,\forall}}$ is the result of replacing X_i by K_i and A_i by A_i^* in $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A,\forall}}$ (except that the analogue of XA is not needed). Finally, let $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}}$ consist of the axioms and rules in $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*,\forall}}$ except for the ones that mention quantification; that is, $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} = \{$Prop, AGPP*, K, Gen*, A0$^*\}$. We use $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}}$ to compare our results to those of HMS.

Theorem 4.3:

(a) $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,X,A,A^*,\forall}} \cup \{\mathrm{T},4,5^*\}$ is a sound and complete axiomatization of the sentences in $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ with respect to $\mathcal{N}_n^{r,e,t}(\Phi,\mathcal{X})$.

(b) $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*,\forall}} \cup \{\mathrm{T},4,5^*\}$ is a sound and complete axiomatization of the sentences in $\mathcal{L}_n^{\forall,K}(\Phi,\mathcal{X})$ with respect to $\mathcal{N}_n^{r,t,e}(\Phi,\mathcal{X})$.

(c) $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T},4,5^*\}$ is a sound and complete axiomatization of $\mathcal{L}_n^{K}(\Phi)$ with respect to $\mathcal{N}_n^{r,t,e}(\Phi)$.

Since, as we observed above, $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*,\forall}}$ is essentially the result of replacing X_i by K_i and A_i by A_i^* in $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A,\forall}}$, Theorem 4.3(b) makes precise the sense in which K_i acts like X_i with respect to A_i^*.

5 DISCUSSION

Just as in our framework, in the HMS and MR approach, a (propositional) language is associated with each world. However, HMS and MR define awareness of φ as an abbreviation of $K_i\varphi \vee K_i\neg K_i\varphi$. In order to compare our approach to that of HMS and MR, we first compare the definitions of awareness. Let $A_i'\varphi$ be an abbreviation for the formula $K_i\varphi \vee K_i\neg K_i\varphi$. The following result says that for extended awareness structures that are Euclidean, $A_i^*\varphi$ is equivalent to $A_i'\varphi$.

Proposition 5.1 : *If $M = (S,\mathcal{L},\pi,\mathcal{K}_1,...,\mathcal{K}_n, \mathcal{A}_1,\ldots,\mathcal{A}_n)$ is a Euclidean extended awareness structure, then for all $s \in S$ and all sentences $\varphi \in \mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$,*

$$(M,s) \models A_i^*\varphi \Leftrightarrow A_i'\varphi.$$

Proof: Suppose that $(M,s) \models K_i(\varphi \vee \neg\varphi) \wedge \neg K_i\varphi$. It follows that $\Phi(\varphi) \subseteq \mathcal{L}(s)$, $\Phi(\varphi) \subseteq \mathcal{L}(t)$ for all t such that $(s,t) \in \mathcal{K}_i$, and that there exists a world t such that $(s,t) \in \mathcal{K}_i$ and $(M,t) \models \neg\varphi$. Let u be an arbitrary world such that $(s,u) \in \mathcal{K}_i$. Since $\mathcal{K}_i$ is Euclidean, it follows that $(u,t) \in \mathcal{K}_i$. Thus, $(M,u) \models \neg K_i\varphi$, so $(M,s) \models K_i\neg K_i\varphi$. It follows that $(M,s) \models A_i'\varphi$, as desired.

For the converse, suppose that $(M,s) \models A_i'\varphi$. If either $(M,s) \models K_i\varphi$ or $(M,s) \models K_i\neg K_i\varphi$, then $\Phi(\varphi) \subseteq \mathcal{L}(s)$, and if $(s,t) \in \mathcal{K}_i$, we have that $\Phi(\varphi) \subseteq \mathcal{L}(t)$. Therefore, $(M,s) \models A_i^*\varphi$. ∎

In [Halpern and Rêgo 2008], we showed that $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T},4,5^*\}$ provides a sound and complete axiomatization of the structures used by HMS where the possibility relations are Euclidean, transitive, and reflexive, with one difference: A_i' is used for awareness instead of A_i^*. However, by Proposition 5.1, in $\mathcal{N}_n^e$, A_i^* and

A_i' are equivalent. Thus, for the class of structures of most interest, we are able to get all the properties of the HMS approach; moreover, we can extend to allow for reasoning about knowledge of unawareness. It is not clear how to capture knowledge of unawareness directly in the HMS approach.

It remains to consider the relationship between A_i and A_i^*. Let $\mathcal{A}_i^*(s)$ be the set of sentences that are defined at all worlds considered possible by agent i in world s; that is, $\varphi \in \mathcal{A}_i^*(s)$ iff $(M,s) \models A_i^*\varphi$. Assuming that agents know what they are aware of, we have that if $(s,t) \in \mathcal{K}_i$, then $\mathcal{A}_i(s) = \mathcal{A}_i(t)$. Thus, it follows that $\mathcal{A}_i(s) \subseteq \mathcal{A}_i^*(s)$. For if $\varphi \in \mathcal{A}_i(s)$, then $\Phi(\varphi) \subseteq \mathcal{L}(t)$ for all t such that $(s,t) \in \mathcal{K}_i$, so $(M,s) \models A_i^*(\varphi)$.

We get the opposite inclusion by assuming the following natural connection between an agent's awareness function and the language in the worlds that he considers possible:

- **LA:** If $p \notin \mathcal{A}_i(s)$, then $p \notin \mathcal{L}(t)$ for some t such that $(s,t) \in \mathcal{K}_i$.

It is immediate that in models that satisfy **LA** (and *agpp*), $\mathcal{A}_i(s) \supseteq \mathcal{A}_i^*(s)$ for all agents i and worlds s. Thus, under minimal assumptions, $\mathcal{A}_i^*(s) = \mathcal{A}_i(s)$.

The bottom line here is that under the standard assumptions in the economics literature, together with the minimal assumption **LA**, all the notions of awareness coincide. We do not need to consider a syntactic notion of awareness at all. However, as pointed out by FH, there are other notions of awareness that may be relevant; in particular, a more computational notion of awareness is of interest. For such a notion, an axiom such as AGPP does not seem appropriate. We leave the problem of finding axioms that characterize a more computational notion of awareness in this framework to future work.

We conclude with some comments on awareness and language. If we think of propositions $p \in \mathcal{L}(t) - \mathcal{A}_i(s)$ as just being labels or names for concepts that agent i is not aware of but i understands other agents might be aware of, **LA** is just saying that i should not use the same label in all worlds that he considers possible. It is important that an agent can use different labels for formulas that he is unaware of. A world where an agent is unaware of two primitive propositions is different from a world where an agent is unaware of only one primitive proposition. For example, to express the fact that in world s agent agent 1 considers it possible that (1) there is a formula that he is unaware that agent 2 is aware of and (2) there is a formula that both he and agent 2 are unaware of that agent 3 is aware of, agent 1 needs to consider possible a world t with at least two primitive propositions in $\mathcal{L}(t) - \mathcal{A}_1(s)$. Needless to say, reasoning about such lack of awareness might be critical in a decision-theoretic context.

The fact that the primitive propositions that an agent is not aware of are simply labels means that switching the labels does not affect what the agent knows or believes. More precisely, given a model $M = (S, \mathcal{L}, \mathcal{K}_1, \ldots, \mathcal{K}_n, \mathcal{A}_1, \ldots, \mathcal{A}_n, \pi)$, let M' be identical to M except that the roles of the primitive propositions p and p' are interchanged. More formally, $M' = (S, \mathcal{L}', \mathcal{K}_1, \ldots, \mathcal{K}_n, \mathcal{A}_1', \ldots, \mathcal{A}_n', \pi')$, where, for all worlds $s \in S$, we have

- $\mathcal{L}(s) - \{p, p'\} = \mathcal{L}'(s) - \{p, p'\}$;
- $p \in \mathcal{L}'(s)$ iff $p' \in \mathcal{L}(s)$, and $p' \in \mathcal{L}'(s)$ iff $p \in \mathcal{L}(s)$;
- $\pi(s,q) = \pi'(s,q)$ for all $q \in \mathcal{L}(s) - \{p, p'\}$;
- if $p \in \mathcal{L}(s)$, then $\pi(s,p) = \pi'(s,p')$, and if $p' \in \mathcal{L}(s)$, then $\pi(s,p') = \pi'(s,p)$;
- if φ is a formula that mentions neither p nor p', then $\varphi \in \mathcal{A}_i(s)$ iff $\varphi \in \mathcal{A}_i'(s)$;
- for any formula φ that mentions either p or p', $\varphi \in \mathcal{A}_i(s)$ iff $\varphi[p \leftrightarrow p'] \in \mathcal{A}_i'(s)$, where $\varphi[p \leftrightarrow p']$ is the result of replacing all occurrences of p in φ by p' and all occurrences of p' by p.

It is easy to see that for all worlds s, $(M,s) \models \varphi$ iff $(M',s) \models \varphi[p \leftrightarrow p']$. In particular, this means that if neither p nor p' is in $\mathcal{L}(s)$, then for all formulas, $(M,s) \models \varphi$ iff $(M',s) \models \varphi$. Thus, switching labels of propositions that are not in $\mathcal{L}(s)$ has no impact on what is true at s.

We remark that the use of labels here is similar in spirit to our use of *virtual moves* in [Halpern and Rêgo 2006a] to model moves that a player is aware that he is unaware of.

Although switching labels of propositions that are not in $\mathcal{L}(s)$ has no impact on what is true at s, changing the truth value of a primitive proposition that an agent is not aware at s may have some impact on what the agent explicitly knows at s. Note that we allow agents to have some partial information about formulas that they are unaware of. We certainly want to allow agent 1 to know that there is a formula that agent 2 is aware of that he (agent 1) is unaware of; indeed, capturing a situation like this was one of our primary motivations for introducing knowledge of lack of awareness. But we also want to allow agent 1 to know that agent 2 is not only aware of the formula, but knows that it is true; that is, we want $X_1(\exists x(\neg A_1(x) \wedge K_2(x)))$ to be consistent. There may come a point when an agent has so much partial information about a formula he is unaware of that, although he cannot talk about it explicitly in his language, he can describe it sufficiently well to communicate about it. When this happens in natural language, people will come up with a name for a concept and add it to their language. We have not addressed the dynamics of language change here, but we believe that this is a topic that deserves further research.

A PROOFS

We first prove Theorem 4.1. As we said in the main text, proving soundness turns out to be nontrivial, so we being by showing that MP, Barcan$^*_X$, and Gen$_\forall$ are sound. (Soundness of the remaining axioms is straightforward. For MP, we need some preliminary lemmas.

Lemma A.1: *If φ is a sentence in $\mathcal{L}_n^{\forall,K,X,A}(\Phi,\mathcal{X})$ that does not mention q and is satisfiable in $\mathcal{N}_n(\Phi,\mathcal{X})$, then it is satisfiable in an extended awareness structure $M = (S,\mathcal{L}(s),\pi,\mathcal{K}_1,\ldots,\mathcal{K}_n,\mathcal{A}_1,\ldots,\mathcal{A}_n) \in \mathcal{N}_n(\Phi,\mathcal{X})$ such that $q \notin \mathcal{L}(s)$ for every $s \in S$.*

Proof: Let $\tau : \Phi \rightarrow \Phi$ be a 1-1 function. For a sentence ψ, let $\tau(\psi)$ be the result of replacing every primitive proposition q in ψ by $\tau(q)$. Given an extended awareness structure $M^\tau(S,\mathcal{L}(s),\pi,\mathcal{K}_1,\ldots,\mathcal{K}_n,\mathcal{A}_1,\ldots,\mathcal{A}_n)$, let $M' = (S,\mathcal{L}^\tau(s),\pi^\tau,\mathcal{K}_1,\ldots,\mathcal{K}_n,\mathcal{A}_1^\tau,\ldots,\mathcal{A}_n^\tau)$ be the extended awareness structure that results from "translating" M by τ; formally: $\mathcal{L}'(s) = \{\tau(p) : p \in \mathcal{L}(s)\}$, $\pi'(s,\tau(p)) = \pi(s,p)$, and $\mathcal{A}_i'(s) = \{\tau(\psi) : \psi \in \mathcal{A}_i(s)\}$. We now prove that $(M,s) \models \psi$ iff $(M^\tau,s) \models \tau(\psi)$ by induction in the structure of ψ. All the cases are straightforward and left to the reader except the case ψ has the form $\forall x\psi'$. In this case, we have that $(M,s) \models \psi$ iff $(M,s) \models \psi'[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$. By the induction hypothesis, $(M,s) \models \psi'[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$ iff $(M^\tau,s) \models \tau(\psi'[x/\beta])$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$. Since $\tau(\psi'[x/\beta]) = \tau(\psi')[x/\tau(\beta)]$ and, by construction of $\mathcal{L}^\tau$, for all $\gamma \in \mathcal{L}_n^{K,X,A}(\mathcal{L}^\tau(s))$ there exists $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$ such that $\gamma = \tau(\beta)$, it follows that $(M^\tau,s) \models \tau(\psi'[x/\beta])$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$ iff $(M^\tau,s) \models \tau(\psi')[x/\gamma])$ for all $\gamma \in \mathcal{L}_n^{K,X,A}(\mathcal{L}^\tau(s))$. The latter statement is true iff $(M^\tau,s) \models \tau(\psi)$.

To complete the proof of the lemma, suppose that φ is a sentence that does not mention q and that $(M,s) \models \varphi$. Let τ be a 1-1 function such that $\tau(p) = p$ for every p that occurs in φ and such that there exists no $r \in \Phi$ such that $\tau(r) = q$. (Here we are using the fact that Φ is an infinite set.) Note that $\varphi = \tau(\varphi)$. Thus, the claim implies that $(M',s) \models \varphi$ and by construction $q \notin \mathcal{L}'(s)$ for every $s \in S$. ∎

Substitution is a standard property of most propositional logics. It says that if φ is valid, then so is $\varphi[q/\psi]$. Substitution in full generality is not valid in our framework, because of the semantics of quantification. For example, although $\forall x \neg A_i x \Rightarrow \neg A_i q$ is valid, $\forall x \neg A_i x \Rightarrow \neg A_i(\forall x A_i x)$ is not. As we now show, if we restrict to quantifier-free substitutions, we preserve validity. But this result depends on the fact that Φ is infinite. For example, if $\Phi = \{p,q\}$, then $\varphi = A_i p \wedge A_i q \Rightarrow \forall x A_i x$ is valid, but $\varphi[q/p] = A_i p \wedge A_i p \Rightarrow \forall x A_i x$ is not valid. We first prove that a slightly weaker version of Substitution holds (in which q cannot appear in ψ), and then prove Substitution.

Proposition A.2: (Weak Substitution) *If φ is a sentence valid in $\mathcal{N}_n(\Phi,\mathcal{X})$, q is a primitive proposition, and ψ is an arbitrary quantifier-free sentence that does not mention q, then $\varphi[q/\psi]$ is valid in $\mathcal{N}_n(\Phi,\mathcal{X})$.*

Proof: Suppose, by way of contradiction, that $\varphi[q/\psi]$ is not valid. Then $\neg\varphi[q/\psi]$ is satisfiable. By Lemma A.1, there exists an extended awareness structure $M = (S,\mathcal{L}(s),\pi,\mathcal{K}_1,\ldots,\mathcal{K}_n,\mathcal{A}_1,\ldots,\mathcal{A}_n)$ and a world $s^* \in S$ such that $(M,s^*) \models \neg\varphi[q/\psi]$ and $q \notin \mathcal{L}(s)$ for every $s \in S$. Let M' extends M by defining q as ψ; more precisely, $M' = (S,\mathcal{L}',\pi',\mathcal{K}_1,\ldots,\mathcal{K}_n,\mathcal{A}_1',\ldots,\mathcal{A}_n')$, where

- $\mathcal{L}'(s) = \mathcal{L}(s) \cup \{q\}$ if $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$, and $\mathcal{L}'(s) = \mathcal{L}(s)$ otherwise;
- $\pi'(s,p) = \pi(s,p)$ for every $p \in \mathcal{L}(s)$ and if $q \in \mathcal{L}'(s)$, then $\pi'(s,q) =$ **true** iff $(M,s) \models \psi$;
- $\mathcal{A}_i'(s) = \mathcal{A}_i(s)$ if $\psi \notin \mathcal{A}_i(s)$, and $\mathcal{A}_i'(s)$ is the smallest set generated by primitive propositions that includes $\mathcal{A}_i(s) \cup \{q\}$ otherwise.

Intuitively, we are just extending M by defining q so that it agrees with ψ everywhere. We claim that for every sentence σ, if $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$, then the following are equivalent:

(a) $(M',s) \models \sigma$

(b) $(M',s) \models \sigma[q/\psi]$

(c) $(M,s) \models \sigma[q/\psi]$.

We first observe that if σ' is a quantifier-free sentence that does not mention q, then for all worlds $s \in S$, we have that $(M,s) \models \sigma$ iff $(M',s) \models \sigma'$. (The formal proof is by a straightforward induction on σ'.

We now prove the claim by induction in the structure of σ. For the base case, note that if σ is the primitive proposition q, then the equivalence between (b) and (c) follows from the observation above.

All cases are straightforward except the case where σ has the form $\forall x\sigma'$. To see that (a) implies (b), suppose that $(M', s) \models \forall x\sigma'$. Then $(M', s) \models \sigma'[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}'(s))$. By the induction hypothesis, $(M', s) \models (\sigma'[x/\beta])[q/\psi]$. Note that $\sigma'[x/\beta][q/\sigma] = ((\sigma'[q/\psi])[x/\beta])[q/\psi]$. Thus, applying the induction hypothesis again, it follows that $(M', s) \models (\sigma'[q/\psi])[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}'(s))$. Therefore, $(M', s) \models \forall x\sigma'[q/\psi]$. This shows that (a) implies (b).

To see that (b) implies (c), suppose that $(M', s) \models \forall x\sigma'[q/\psi]$. Thus, $(M', s) \models (\sigma'[q/\psi])[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}'(s))$. Since $\mathcal{L}_n^{K,X,A}(\mathcal{L}(s)) \subseteq \mathcal{L}_n^{K,X,A}(\mathcal{L}'(s))$, by the induction hypothesis, it follows that $(M, s) \models (\sigma'[q/\psi])[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$. Thus, $(M, s) \models \forall x\sigma'[q/\psi]$.

Finally, to see that (c) implies (a), suppose that $(M, s) \models \forall x\sigma'[q/\psi]$. We want to show that $(M', s) \models \forall x\sigma'$, or equivalently, that $(M', s) \models \sigma'[x/\beta]$ for all $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s'))$. Choose $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s'))$. So choose $\beta \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s'))$. By the induction hypothesis, $(M', s) \models \sigma'[x/\beta]$ iff $(M', s) \models (\sigma'[x/\beta])[q/\psi]$ iff $(M, s) \models (\sigma'[x/\beta])[q/\psi]$. Since $(\sigma'[x/\beta])[q/\psi] = \sigma'[q/\sigma](x/\beta[q/\sigma])$, and $(M, s) \models \sigma'[q/\sigma](x/\beta[q/\sigma])$ since $(M, s) \models \forall x\sigma'[q/\sigma]$, by assumption, the desired result follows.

Since, by assumption, $(M, s^*) \models \neg\varphi[q/\psi]$, it follows from the claim above that $(M', s^*) \models \neg\varphi$, a contradiction. ▮

Corollary A.3: (Substitution) *If φ is a sentence valid in $\mathcal{N}_n(\Phi, \mathcal{X})$, q is a primitive proposition, and ψ is an arbitrary quantifier-free sentence, then $\varphi[q/\psi]$ is valid in $\mathcal{N}_n(\Phi, \mathcal{X})$.*

Proof: Choose a primitive proposition r that does not appear in ψ or φ. By Weak Substitution (Proposition A.2), $\varphi' = \varphi[q/r]$ is valid. Applying Weak Substitution again, $\varphi'[r/\psi] = \varphi[q/\psi]$ is valid. ▮

We are finally ready to prove the soundness of MP.

Corollary A.4: *If $\varphi \Rightarrow \psi$ and φ are both valid in an awareness structure M, then so is φ.*

Proof: Suppose, by way of contradiction, then $\varphi \Rightarrow \psi$ and φ are valid in M, and, for some world s in M, we have that $(M, s) \models \neg\varphi$. It must be the case that $\psi \notin \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s), \mathcal{X})$, while $\varphi \in \mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s), \mathcal{X})$. Let $q_1, \ldots, q_k$ be the primitive propositions that are mentioned in ψ but are not in $\mathcal{L}(s)$. Note that none of $q_1, \ldots, q_k$ can appear in φ. Since, by assumption, $\mathcal{L}(s)$ is non-empty, let $p \in \mathcal{L}(s)$, and let $\psi' = \psi[q_1/p, \ldots, q_k/p]$. By Weak Substitution, ψ' and $\psi' \Rightarrow \varphi$ are valid. But ψ' and φ are in $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(s), \mathcal{X})$. Thus, we must have $(M, s) \models \psi'$ and $(M, s) \models \psi' \Rightarrow \varphi$, so $(M, s) \models \varphi$, a contradiction. ▮

The following two results prove the soundness of Gen$_\forall$ and Barcan$^*_X$.

Proposition A.5: (Gen$_\forall$) *If φ is a valid sentence in $\mathcal{N}_n(\Phi, \mathcal{X})$ and q is an arbitrary primitive proposition, then $\forall x\varphi[q/x]$ is valid in $\mathcal{N}_n(\Phi, \mathcal{X})$.*

Proof: Suppose not. Then there exists an extended awareness structure in $M \in \mathcal{N}_n(\Phi, \mathcal{X})$ and a world s such that $(M, s) \models \neg\forall x\varphi[q/x]$. Thus, there exists a formula $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$ such that $(M, s) \models \neg(\varphi[q/x])[x/\psi]$. Thus, $\varphi[q/\psi]$ is not valid. By Substitution, it follows that φ is not valid either, a contradiction. ▮

Proposition A.6: (Barcan$^*_X$) *$(A_i(\forall x\varphi) \wedge \forall x(A_i x \Rightarrow X_i\varphi)) \Rightarrow X_i(\forall x A_i x \Rightarrow \forall x\varphi)$ is valid in $\mathcal{N}_n(\Phi, \mathcal{X})$.*

Proof: Suppose that $(M, s) \models (A_i(\forall x\varphi) \wedge \forall x(A_i x \Rightarrow X_i\varphi))$. Since awareness is generated by primitive propositions, $(M, s) \models A_i(\forall x A_i x \Rightarrow \forall x\varphi)$. Suppose, by way of contradiction, that $(M, s) \models \neg X_i(\forall x A_i x \Rightarrow \forall x\varphi)$. Then there must exist some world t such that $(s, t) \in \mathcal{K}_i$ and $(M, t) \models \neg(\forall x A_i x \Rightarrow \forall x\varphi)$. Thus, $(M, t) \models \forall x A_i x$ and $(M, t) \models \neg\forall x\varphi$. Since $(M, t) \models \neg\forall x\varphi$, it follows that there exists $\psi \in \mathcal{L}_n^{X,A}(\mathcal{L}(t))$ such that $(M, t) \models \neg\varphi[x/\psi]$. Since $(M, t) \models \forall x A_i x$, we must have $(M, t) \models A_i\psi$. Since $\mathcal{A}_i(s) = \mathcal{A}_i(t)$, we also have $(M, s) \models A_i\psi$. Since $(M, s) \models \forall x(A_i x \Rightarrow X_i\varphi)$, it follows that $(M, s) \models X_i\varphi[x/\psi]$. Thus, $(M, t) \models \varphi[x/\psi]$, a contradiction. ▮

With these results in hand, we can now prove Theorem 4.1. We repeat the theorem here for the convenience of the reader.

Theorem 4.1: *If $\mathcal{C}_X$ is a (possibly empty) subset of $\{\mathrm{T_X}, 4_\mathrm{X}, 5_\mathrm{X}\}$ and C is the corresponding subset of $\{r, t, e\}$, then $\mathrm{AX}_\mathrm{e}^{\mathrm{X,A},\forall} \cup \mathcal{C}_\mathrm{X}$ is a sound and complete axiomatization of the language $\mathcal{L}_n^{\forall,X,A}(\Phi, \mathcal{X})$ with respect to $\mathcal{N}_n^C(\Phi, \mathcal{X})$.*

Proof: Corollary A.4 and Propositions A.5 and A.6 show the soundness of MP, Gen$_\forall$, and Barcan$^*_X$, respectively. The proof of soundness for the other axioms and rules is standard and left to the reader. The soundness of $\mathrm{AX}_\mathrm{e}^{\mathrm{X,A},\forall} \cup \mathcal{C}_\mathrm{X}$ follows easily.

We now consider completeness. As we said in the main text, the proof is quite similar in spirit to that of Theorem 2.1 given in HR. We focus here on the differences. We give the remainder of the proof only for the case

$\mathcal{C}_X = \emptyset$; the other cases follow using standard techniques (see, for example, [Fagin, Halpern, Moses, and Vardi 1995; Hughes and Cresswell 1996]).

As usual, the idea of the completeness proof is to construct a canonical model M^c where the worlds are maximal consistent sets of sentences. It is then shown that if s_V is the world corresponding to the maximal consistent set V, then $(M^c, s_V) \models \varphi$ iff $\varphi \in V$. As observed in HR, this will not quite work in the presence of quantification, since there may be a maximal consistent set V of sentences such that $\neg\forall x\varphi \in V$, but $\varphi[x/\psi]$ for all $\psi \in \mathcal{L}_n^{K,X,A}(\Phi)$. That is, there is no witness to the falsity of $\forall x\varphi$ in V. This problem was dealt with in HR by restricting to maximal consistent sets V that are *acceptable* in the sense that if $\neg\forall x\varphi \in V$, then $\neg\varphi[x/q] \in V$ for infinitely many primitive propositions $q \in \Phi$. (Note that this notion of acceptability also requires Φ to be infinite.) Because here we have possibly different languages associated different worlds, we need to consider acceptability and maximality with respect to a language.

Definition A.7: A set Γ is *acceptable with respect to* $L \subseteq \Phi$ if $\varphi \in \mathcal{L}_n^{\forall,X,A}(L,\mathcal{X})$ and $\Gamma \vdash \varphi[x/q]$ for all but finitely many primitive propositions $q \in L$, then $\Gamma \vdash \forall x\varphi$. ∎

Definition A.8: If AX is an axiom system, a set Γ is *maximal AX-consistent set of sentences with respect to* $L \subseteq \Phi$ if Γ is a set of sentences contained in $\mathcal{L}_n^{\forall,X,A}(L,\mathcal{X})$ and, for all sentences $\varphi \in \mathcal{L}_n^{\forall,X,A}(L,\mathcal{X})$, if $\Gamma \cup \{\varphi\}$ is AX-consistent, then $\varphi \in \Gamma$. ∎

The following four lemmas are essentially Lemmas A.4, A.5, A.6, and A.7 in HR. Since the proofs are essentially identical, we do not repeat them here.

Lemma A.9: *If Γ is a finite set of sentences, then Γ is acceptable with respect to every subset $L \subseteq \Phi$ that contains infinitely many primitive propositions.*

Lemma A.10: *If Γ is acceptable with respect to L and τ is a sentence in $\mathcal{L}_n^{\forall,X,A}(L,\mathcal{X})$, then $\Gamma \cup \{\tau\}$ is acceptable with respect to L.*

Lemma A.11: *If $\Gamma \subseteq \mathcal{L}_n^{\forall,X,A}(L,\mathcal{X})$ is an acceptable $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent set of sentences with respect to L, then Γ can be extended to a set of sentences that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L.*

Let $\Gamma/X_i = \{\varphi : X_i\varphi \in \Gamma\}$.

Lemma A.12: *If Γ is a a set of sentences that is maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L containing $\neg X_i\varphi$ and $A_i\varphi$, then $\Gamma/X_i \cup \{\neg\varphi\}$ is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent.*

Lemma A.14 in HR shows that if Γ is an acceptable maximal consistent set that contains $A_i\varphi$ and $\neg X_i\varphi$, then $\Gamma/X_i \cup \{\neg\varphi\}$ can be extended to an acceptable maximal consistent set Δ. (Lemma A.8 proves a similar result for the K_i operator.) The following lemma proves an analogous result, but here we must work harder to take the language into account. That is, we have to define the language L' with respect to which Δ is maximal and acceptable. As usual, we say that L is *co-infinite* if $\Phi - L$ is infinite.

Lemma A.13 : *If Γ is an acceptable maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent set of sentences with respect to L, where L is infinite and co-infinite, $\neg X_i\varphi \in \Gamma$, and $A_i\varphi \in \Gamma$, then there exist an infinite and co-infinite set $L' \subseteq \Phi$ and a set Δ of sentences that is acceptable, maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L' and contains $\Gamma/X_i \cup \{\neg\varphi\}$. Moreover, $A_i\psi \in \Delta$ iff $A_i\psi \in \Gamma$ for all formulas ψ.*

Proof: By Lemma A.12, $\Gamma/X_i \cup \{\neg\varphi\}$ is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent. We define a subset $L' \subseteq \Phi$ and construct a set Δ of sentences that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L' such that Δ contains $\Gamma/X_i \cup \{\neg\varphi\}$ and $A_i\varphi \in \Delta$ iff $A_i\varphi \in \Gamma$ for all formulas φ.

We consider two cases: (1) $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x A_i x$; and (2) $\Gamma/X_i \cup \{\neg\varphi\} \not\vdash \forall x A_i x$.

If $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x A_i x$, then define $L' = \{q : A_i q \in \Gamma\}$. Note that since $\Gamma \vdash A_i\varphi$, it follows that every primitive proposition q in φ must be in L', as is every primitive proposition in a formula in Γ/X_i. L' must be infinite, for if it were finite, then we would have that $\Gamma \vdash A_i q$ for only finitely many primitive propositions in L. Since Γ is a maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent set, it must be the case that $\Gamma \vdash \neg A_i q$ for all but finitely many primitive propositions $q \in L$. Since Γ is acceptable with respect to L, $\Gamma \vdash \forall x \neg A_i x$. Thus, axiom FA_X^* implies that $\forall x \neg A_i x \in \Gamma/X_i$, which is a contradiction, since by assumption $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x A_i x$. Thus, L' must be infinite. Since L' is a subset of L, it is clearly co-infinite, since L is.

We prove that $\Gamma/X_i \cup \{\neg\varphi\}$ is acceptable with respect to L' in this case. Suppose that $\psi \in \mathcal{L}_n^{\forall,X,A}(L',\mathcal{X})$ and

$$\Gamma/X_i \cup \{\neg\varphi\} \vdash \psi[x/q] \text{ for all but finitely many } q \in L'. \quad (1)$$

We want to show that $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x\psi$. It follows from (1) that $\Gamma/X_i \vdash \neg\varphi \Rightarrow \psi[x/q]$ for all but finitely many $q \in L'$. Since every primitive proposition in ψ is in $L' = \{q : A_i q \in \Gamma\}$, and $A_i\varphi \in \Gamma$, it easily follows that $\Gamma \vdash X_i(\neg\varphi \Rightarrow \psi[x/q])$ for all but finitely many $q \in L'$. Since $L' = \{q : A_i q \in \Gamma\}$, it follows that $\Gamma \vdash A_i q \Rightarrow X_i(\neg\varphi \Rightarrow \psi[x/q])$ for all but finitely many

$q \in L$. Since Γ is acceptable with respect to L, we have that

$$\Gamma \vdash \forall x(A_i x \Rightarrow X_i(\neg\varphi \Rightarrow \psi)). \quad (2)$$

Again using the fact that $\Gamma \vdash A_i q$ for all q in ψ and $\Gamma \vdash A_i\varphi$, from AGPP we have that

$$\Gamma \vdash A_i \forall x(\neg\varphi \Rightarrow \psi). \quad (3)$$

From Barcan$^*_X$, (2), and (3), it follows that $\Gamma \vdash X_i(\forall x A_i x \Rightarrow \forall x(\neg\varphi \Rightarrow \psi))$. Thus, $\Gamma/X_i \vdash \forall x A_i x \Rightarrow \forall x(\neg\varphi \Rightarrow \psi)$. Since $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x A_i x$, it follows that $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x(\neg\varphi \Rightarrow \psi)$. Since φ is a sentence, applying $K_\forall$ and $N_\forall$, it easily follows that $\Gamma/X_i \cup \{\neg\varphi\} \vdash \neg\varphi \Rightarrow \forall x\psi$. Thus, $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x\psi$, as desired.

Therefore, $\Gamma/X_i \cup \{\neg\varphi\}$ is a set of sentences that is acceptable with respect to L' and $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent. Thus, by Lemma A.11, there exists a set of sentences Δ containing $\Gamma/X_i \cup \{\neg\varphi\}$ that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L'. Finally, we prove that $A_i\psi \in \Gamma$ iff $A_i\psi \in \Delta$. First, suppose that $A_i\psi \in \Gamma$. Then, XA implies that $X_i A_i \psi \in \Gamma$. Thus, $A_i\psi \in \Gamma/X_i \subseteq \Delta$. For the converse, suppose that $A_i\psi \in \Delta$. Since $\psi \in \mathcal{L}_n^{\forall,X,A}(L', \mathcal{X})$, it must be the case that $\Gamma \vdash A_i q$ for every primitive proposition q that appears in ψ; thus $\Gamma \vdash A_i\psi$.

If $\Gamma/X_i \cup \{\neg\varphi\} \not\vdash \forall x A_i x$, define $L' = \{q : A_i q \in \Gamma\} \cup L''$, where L'' is an infinite and co-infinite set of primitive propositions not occurring in $\Gamma \cup \{\varphi\}$ (which exists, since, by assumption, $\Phi - L$ is infinite). It can be easily seen that L' is infinite and co-infinite. Since $\Gamma/X_i \cup \{\neg\varphi\}$ is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent, $\Gamma/X_i \cup \{\neg\varphi\} \not\vdash \forall x A_i x$ implies that $\Gamma/X_i \cup \{\neg\varphi, \neg\forall x A_i x\}$ is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent.

To see that $\Gamma/X_i \cup \{\neg\varphi\}$ is acceptable with respect to L', suppose that $\psi \in \mathcal{L}_n^{\forall,X,A}(L', \mathcal{X})$ and $\Gamma/X_i \cup \{\neg\varphi\} \vdash \psi[x/q]$ for all but finitely many $q \in L'$. There must be some $q \in L'$ not mentioned in Γ/X_i or φ such that $\Gamma/X_i \cup \{\neg\varphi\} \vdash \psi[x/q]$. Since $\Gamma/X_i \cup \{\neg\varphi\} \vdash \psi[x/q]$, it follows that there exists a subset $\{\beta_1 \ldots, \beta_n\} \subseteq \Gamma/X_i \cup \{\neg\varphi\}$ such that $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall} \vdash \beta \Rightarrow \psi[\mathrm{x/q}]$, where $\beta = \beta_1 \wedge \cdots \wedge \beta_n$. Since q does not occur in β or φ, by Gen$_\forall$, we have $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall} \vdash \forall \mathrm{x}(\beta \Rightarrow \psi)$. Since β is a sentence, applying $K_\forall$ and $N_\forall$, it easily follows that $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall} \vdash \beta \Rightarrow \forall \mathrm{x}\psi$, which implies that $\Gamma/X_i \cup \{\neg\varphi\} \vdash \forall x\psi$, as desired. Finally, since $\Gamma/X_i \cup \{\neg\varphi\}$ is acceptable with respect to L', Lemma A.10 implies that $\Gamma/X_i \cup \{\neg\varphi, \neg\forall x A_i x\}$ is acceptable with respect to L'.

Let $\psi_1, \psi_2, \ldots$ be an enumeration of the set of sentences in $\mathcal{L}_n^{\forall,X,A}(L', \mathcal{X})$ such that if ψ_k is of the form $\neg\forall x\varphi$, then there must exist a $j < k$ such that ψ_j is of the form $\forall x\varphi$ and if ψ_k is a formula that contains a primitive proposition $q \in L''$, then there must exist a $j < k$ such that ψ_j is of the form $\neg A_i q$. The construction continues exactly as in the proof of Lemma A.11, where we take $\Delta_0 = \Gamma/X_i \cup \{\neg\varphi, \neg\forall x A_i x\}$. Note that by construction, if $\psi_j = \neg A_i q$ for some $q \in L''$, then q does not occur in Δ'_{j-1}. We claim that $\Delta'_{j-1} \cup \{\neg A_i q\}$ is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent. For suppose otherwise. Then, as above, there exists a subset $\{\beta_1, \ldots, \beta_n\} \subseteq \Delta'_{j-1}$ such that $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall} \vdash \beta \Rightarrow \forall \mathrm{x} \mathrm{A_i} \mathrm{x}$ Since $\{\beta_1, \ldots, \beta_n, \neg\forall x A_i x\} \subseteq \Delta'_{j-1}$, it follows that Δ'_{j-1} is not $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent, a contradiction.

Therefore, Δ is a set of sentences that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L' and includes $\Gamma/X_i \cup \neg\varphi \cup \{\neg A_i q : q \in L''\}$. The proof that $A_i\psi \in \Gamma$ implies $A_i\psi \in \Delta$ is identical to the first case. For the converse, suppose that $A_i\psi \in \Delta$. Then, by AGPP, $A_i q \in \Delta$ for all primitive propositions q that appear in ψ. The construction of Δ guarantees that, for all primitive propositions in L', we have $A_i q \in \Delta$ iff $A_i q \in \Gamma$. Since Γ is maximal $\mathbf{X}_{\mathbf{n}}^{\forall}$-consistent with respect to L, AGPP implies that $A_i\psi \in \Gamma$. ∎

Lemma A.14: *If φ is a $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent sentence, then φ is satisfiable in $\mathcal{N}_n^{agpp,ka,\emptyset}(\Phi, \mathcal{X})$.*

Proof: As usual, we construct a canonical model where the worlds are maximal consistent sets of formulas. However, now the worlds must also explicitly include the language. For technical reasons, we also assume that the language is infinite and coninfinite.

Let $M^c = (S, \mathcal{L}, \mathcal{K}_1, ..., \mathcal{K}_n, \mathcal{A}_1, \ldots, \mathcal{A}_n, \pi)$ be a canonical extended awareness structure constructed as follows

- $S = \{(s_V, L) :$ V is a set of sentences that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L, where $L \subseteq \Phi$ is infinite and co-infinite$\}$;
- $\mathcal{L}((s_V, L)) = L$;
- $\pi((s_V, L), p) = \begin{cases} \textbf{true} & \text{if } p \in V, \\ \textbf{false} & \text{if } p \in (L - V); \end{cases}$
- $\mathcal{A}_i((s_V, L)) = \{\varphi : A_i\varphi \in V\}$;
- $\mathcal{K}_i((s_V, L)) = \{(s_W, L') : V/X_i \subseteq W$ and $A_i\varphi \in W$ iff $A_i\varphi \in V$ for all formulas $\varphi\}$.

We show that if $\psi \in \mathcal{L}_n^{\forall,X,A}(L, \mathcal{X})$ is a sentence, then

$$(M^c, (s_V, L)) \models \psi \ \text{ iff } \ \psi \in V. \quad (4)$$

Note that this claim suffices to prove Lemma A.14 since, for all $L \subseteq \Phi$ that is infinite and co-infinite, if $\varphi \in \mathcal{L}_n^{\forall,X,A}(L, \mathcal{X})$ is a $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent sentence, by Lemmas A.9 and A.11, it is contained in a set of sentences that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L.

We prove (4) by induction of the depth of nesting of $\forall$, with a subinduction on the length of the sentence. The details are standard and left to the reader. For the case of $X_i\varphi$, we need Lemma A.13.

If φ is consistent, by Lemmas A.9 and A.11, then φ there is a set $L \subseteq \Phi$ that is infinite and co-infinite and contains $\Phi(\varphi)$ and a set V of sentences that is acceptable and maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent with respect to L such that $\varphi \in V$. By the argument above, $(M, (s_V, L)) \models \varphi$, showing that φ is satisfiable, as desired. ∎

To finish the completeness proof, suppose that φ is valid in $\mathcal{N}_n^{agpp,ka,\emptyset}(\Phi, \mathcal{X})$. Since φ is a sentence, it follows that $\neg\varphi$ is a sentence and is not satisfiable in $\mathcal{N}_n^{agpp,ka,\emptyset}(\Phi, \mathcal{X})$. So, by Lemma A.14, $\neg\varphi$ is not $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$-consistent. Thus, φ is provable in $\mathrm{AX}_{\mathrm{e}}^{\mathrm{X,A},\forall}$. ∎

Proposition 4.2:

(a) XA is valid in* $\mathcal{N}_n^t(\Phi, \mathcal{X})$.

(b) Barcan is valid in* $\mathcal{N}_n^{r,e}(\Phi, \mathcal{X})$.

(c) FA is valid in* $\mathcal{N}_n^{r,e}(\Phi, \mathcal{X})$.

(d) 5 is valid in* $\mathcal{N}_n^{e}(\Phi, \mathcal{X})$.

Proof: For part (a), suppose that $(M, s) \models A_i^*\varphi$, where $M \in \mathcal{N}_n^t(\Phi, \mathcal{X})$. Thus, $(M, s) \models K_i(\varphi \vee \neg\varphi)$. Since the axiom 4 is valid in structures in $\mathcal{N}_n^t(\Phi, \mathcal{X})$, it follows that $(M, s) \models K_iK_i(\varphi \vee \neg\varphi)$, that is, $(M, s) \models K_iA_i^*\varphi$.

For part (b), suppose that $(M, s) \models A_i^*(\forall x\varphi) \wedge \forall x(A_i^*x \Rightarrow K_i\varphi)$, where $M \in \mathcal{N}_n^{r,e}(\Phi, \mathcal{X})$. It easily follows that $(M, s) \models A_i^*(\forall x A_i^* x \Rightarrow \forall x\varphi)$. Suppose, by way of contradiction, that $(M, s) \models \neg K_i(\forall x A_i^* x \Rightarrow \forall x\varphi)$. Then there must exist some world t such that $(s, t) \in \mathcal{K}_i$ and $(M, t) \models \neg(\forall x A_i^* x \Rightarrow \forall x\varphi)$. Thus, $(M, t) \models \forall x A_i^* x$ and $(M, t) \models \neg\forall x\varphi$. Since $(M, t) \models \neg\forall x\varphi$, it follows that there exists $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(t))$ such that $(M, t) \models \neg\varphi[x/\psi]$. Since $(M, t) \models \forall x A_i^* x$, we must have $(M, t) \models A_i^*\psi$. Thus, for every world u such that $(t, u) \in \mathcal{K}_i$, it follows that $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(u))$. Suppose that $(s, v) \in \mathcal{K}_i$. Since $\mathcal{K}_i$ is Euclidean and $(s, t) \in \mathcal{K}_i$, it follows that $(t, v) \in \mathcal{K}_i$ and, by the observation above, that $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(v))$. Since $\mathcal{K}_i$ is reflexive and Euclidean, it follows that $(t, s) \in \mathcal{K}_i$, so the argument above also shows that $\psi \in \mathcal{L}_n^{K,X,A}(\mathcal{L}(s))$. Thus, $(M, s) \models A_i^*\psi$. Since $(M, s) \models \forall x(A_i^* x \Rightarrow K_i\varphi)$, it follows that $(M, s) \models K_i\varphi[x/\psi]$. Thus, $(M, t) \models \varphi[x/\psi]$, a contradiction.

Finally, for part (c), suppose that $(M, s) \models \forall x \neg A_i^* x$, where $M \in \mathcal{N}_n^{r,e}(\Phi, \mathcal{X})$. Thus, for every primitive proposition $p \in \mathcal{L}(s)$, there exists some t_p such that $(s, t_p) \in \mathcal{K}_i$ and $p \notin \mathcal{L}(t_p)$. Let u be an arbitrary world such that $(s, u) \in \mathcal{K}_i$. Let φ be an arbitrary quantifier-free sentence in $\mathcal{L}_n^{\forall,K,X,A}(\mathcal{L}(u), \mathcal{X})$. If $\Phi(\varphi) \cap \mathcal{L}(s) \neq \emptyset$, suppose that $p \in \Phi(\varphi) \cap \mathcal{L}(s)$. By assumption, $p \notin \mathcal{L}(t_p)$. Since $\mathcal{K}_i$ is Euclidean, $(u, t_p) \in \mathcal{K}_i$. Thus, $(M, u) \models \neg A_i^*\varphi$. If $\Phi(\varphi) \cap \mathcal{L}(s) = \emptyset$, note that since $\mathcal{K}_i$ is reflexive and Euclidean, the fact that (s, s) and (s, u) are in $\mathcal{K}_i$ implies that $(u, s) \in \mathcal{K}_i$. Hence, we again have that $(M, u) \models \neg A_i^*\varphi$.

The proof of part (d) is standard, and left to the reader. ∎

Theorem 4.3:

(a) $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,X,A,A^*},\forall} \cup \{\mathrm{T}, 4, 5^*\}$ *is a sound and complete axiomatization of the sentences in* $\mathcal{L}_n^{\forall,K,X,A}(\Phi, \mathcal{X})$ *with respect to* $\mathcal{N}_n^{r,t,e}(\Phi, \mathcal{X})$.

(b) $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*},\forall} \cup \{\mathrm{T}, 4, 5^*\}$ *is a sound and complete axiomatization of the sentences in* $\mathcal{L}_n^{\forall,K}(\Phi, \mathcal{X})$ *with respect to* $\mathcal{N}_n^{r,t,e}(\Phi, \mathcal{X})$.

(c) $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\}$ *is a sound and complete axiomatization of* $\mathcal{L}_n^{K}(\Phi)$ *with respect to* $\mathcal{N}_n^{r,t,e}(\Phi)$.

Proof:

The proof of part (a) is identical to the proof of Theorem 4.1, except that X_i and A_i are replaced by K_i and A_i^*, respectively, and in Lemma A.14, another step is needed in the induction to deal with X_i that uses the extra axiom A0 in the standard way.

For part (b), note that since X_i and A_i are not part of the language the axioms of $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,X,A,A^*},\forall}$ that mention these operators are not needed in the induction of Lemma A.14. Therefore, the proof is the same.

The proof of part (c) is similar to that of Theorem 4.1, except that the following lemma is used instead of Lemma A.14.

Lemma A.15: *If* φ *is a* $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\}$*-consistent sentence in* $\mathcal{L}_n^{K}(\Phi)$*, then* φ *is satisfiable in* $\mathcal{N}_n^{r,t,e}(\Phi)$.

Proof: Let $M^c = (S, \mathcal{L}, \mathcal{K}_1, ..., \mathcal{K}_n, \mathcal{A}_1, \ldots, \mathcal{A}_n, \pi)$ be a canonical extended awareness structure constructed as follows

- $S = \{(s_V, L) : V$ is a set of sentences in $\mathcal{L}_n^K(L)$ that is maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\}$-consistent with respect to L and $L \subseteq \Phi\}$;
- $\mathcal{L}((s_V, L)) = L$;

- $\pi((s_V, L), p) = \begin{cases} \textbf{true} & \text{if } p \in V, \\ \textbf{false} & \text{if } p \in (L - V); \end{cases}$
- $\mathcal{A}_i((s_V, L))$ is arbitrary;
- $\mathcal{K}_i((s_V, L)) = \{(s_W, L) : V/K_i \subseteq W\}$.

It is easy to see that $M^c \in \mathcal{N}_n^{r,t,e}(\Phi)$. As usual, to prove Lemma A.15, we now show that for every $\psi \in \mathcal{L}_n^K(L)$,

$$(M^c, (s_V, L)) \models \psi \text{ iff } \psi \in V. \quad (5)$$

We prove (5) by induction on the length of the formula. All the cases are standard, except for the case that $\psi = K_i\psi'$. In this case, if $\psi \in V$, then $\psi' \in W$ for every W such that $(s_W, L') \in \mathcal{K}_i((s_V, L))$. By the induction hypothesis, $(M^c, (s_W, L')) \models \psi'$ for every $(s_W, L') \in \mathcal{K}_i((s_V, L))$, so $(M^c, (s_V, L)) \models K_i\psi'$.

If $\psi \notin V$, since $\psi \in \mathcal{L}_n^K(L)$, it follows that $\neg\psi \in V$. If $A_i^*\psi' \notin V$, then ψ' is not defined at some world $(s_W, L') \in \mathcal{K}_i((s_V, L))$ which implies that $(M^c, (s_V, L)) \not\models \psi$. If $A_i^*\psi' \in V$, then we need to show that $V/K_i \cup \{\neg\psi'\}$ is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\}$-consistent. Suppose not. Then there exists a subset $\{\beta_1, \ldots, \beta_k\} \subseteq V/K_i$ such that

$$\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\} \vdash \beta \Rightarrow \psi',$$

where $\beta = \beta_1 \wedge \cdots \wedge \beta_k$. By Gen*, it follows that

$$\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\} \vdash \mathrm{A}_{\mathrm{i}}^*(\beta \Rightarrow \psi') \Rightarrow \mathrm{K}_{\mathrm{i}}(\beta \Rightarrow \psi').$$

Since $\{\beta_1, \ldots, \beta_k\} \subseteq V/K_i$, it follows that $\{K_i\beta_1, \ldots, K_i\beta_k\} \subseteq V$. Thus, by A0*, we have $\{A_i^*\beta_1, \ldots, A_i^*\beta_k\} \subseteq V$. Thus, $A_i^*(\beta \Rightarrow \psi') \in V$ and $K_i\beta \in V$. Therefore, $K_i\psi' \in V$, a contradiction.

Since $V/K_i \cup \{\neg\psi'\} \subseteq \mathcal{L}_n^K(L)$ and is $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\}$-consistent, it follows that there exists a set of sentences W that is maximal $\mathrm{AX}_{\mathrm{e}}^{\mathrm{K,A^*}} \cup \{\mathrm{T}, 4, 5^*\}$-consistent with respect to L and contains $V/K_i \cup \{\neg\psi'\}$. Thus, $(s_W, L) \in \mathcal{K}_i((s_V, L))$ and, by the induction hypothesis, $(M^c, (s_W, L)) \not\models \psi'$. Thus, $(M^c, (s_V, L)) \not\models \psi$. ∎

∎

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References

Board, O. and K.-S. Chung (2009). Object-based unawareness: theory and applications. unpublished manuscript.

Fagin, R. and J. Y. Halpern (1988). Belief, awareness, and limited reasoning. *Artificial Intelligence 34*, 39–76.

Fagin, R., J. Y. Halpern, Y. Moses, and M. Y. Vardi (1995). *Reasoning About Knowledge*. Cambridge, Mass.: MIT Press. A slightly revised paperback version was published in 2003.

Halpern, J. Y. (2001). Alternative semantics for unawareness. *Games and Economic Behavior 37*, 321–339.

Halpern, J. Y. and L. C. Rêgo (2006a). Extensive games with possibly unaware players. In *Proc. Fifth International Joint Conference on Autonomous Agents and Multiagent Systems*, pp. 744–751. Full version available at arxiv.org/abs/0704.2014.

Halpern, J. Y. and L. C. Rêgo (2006b). Reasoning about knowledge of unawareness. In *Principles of Knowledge Representation and Reasoning: Proc. Tenth International Conference (KR '06)*, pp. 6–13. To appear, *Games and Economic Behavior.*

Halpern, J. Y. and L. C. Rêgo (2008). Interactive unawareness revisited. *Games and Economic Behavior 62*(1), 232–262.

Heifetz, A., M. Meier, and B. Schipper (2006). Interactive unawareness. *Journal of Economic Theory 130*, 78–94.

Heifetz, A., M. Meier, and B. Schipper (2008). A canonical model for interactive unawareness. *Games and Economic Behavior 62*, 305–324.

Hintikka, J. (1962). *Knowledge and Belief.* Ithaca, N.Y.: Cornell University Press.

Hughes, G. E. and M. J. Cresswell (1996). *A New Introduction to Modal Logic.* London: Routledge.

Modica, S. and A. Rustichini (1994). Awareness and partitional information structures. *Theory and Decision 37*, 107–124.

Modica, S. and A. Rustichini (1999). Unawareness and partitional information structures. *Games and Economic Behavior 27*(2), 265–298.

Sillari, G. (2008). A logic of awareness and impossible possible worlds. *Review of Symbolic Logic 1*(4), 514–529.