Inquisitive Logic as an Epistemic Logic of Knowing How*

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Abstract
In this paper, we present an alternative interpretation of propositional inquisitive logic as an epistemic logic of knowing how. In our setting, an inquisitive logic formula \( \alpha \) being supported by a state is formalized as knowing how to resolve \( \alpha \) (more colloquially, knowing how \( \alpha \) is true) holds on the S5 epistemic model corresponding to the state. Based on this epistemic interpretation, we use a dynamic epistemic logic with both know-how and know-that operators to capture the epistemic information behind the innocent-looking connectives in inquisitive logic. We show that the set of valid know-how formulas corresponds precisely to the inquisitive logic. The main result is a complete axiomatization with intuitive axioms using the full dynamic epistemic language. Moreover, we show that the know-how operator and the dynamic operator can both be eliminated without changing the expressivity over models, which is consistent with the modal translation of inquisitive logic existing in the literature. We hope our framework can give an intuitive alternative interpretation to various concepts and technical results in inquisitive logic, and also provide a powerful and flexible tool to handle both the inquisitive reasoning and declarative reasoning in an epistemic context.

1 Introduction

Inquisitive logic captures the valid reasoning patterns of statements and questions in a neat uniform framework [12]. There are two major views on inquisitive logic: one may view it as a non-classical logic as presented in the early days of the field (cf. e.g., [12]); alternatively, as endorsed by various recent works, one can also view the framework as a conservative extension of classical logic taking the inquisitive disjunction and other machinery as new additions on top of the classical ones (cf. e.g., [6, 7]). According to the first non-classical view, the basic system \textbf{InqB} of propositional inquisitive logic is a weak intermediate logic that includes all the axioms of intuitionistic logic without the axiom of excluded middle, but is not closed under uniform substitution. Moreover, inquisitive logic has some surprising close connections to some other logics such as Medvedev Logic [12], and it can be viewed as a disguised propositional intuitionistic dependence logic [40][11]. The second extension-view gives flexibility in designing logical systems combining the power of both classical reasoning and inquisitive reasoning. As a rapidly growing field of logic, besides being intensively studied itself, inquisitive logic has been extended widely with various modalities and other non-classical connectives (cf. e.g., [13][19][29]).

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The characteristic semantic feature of inquisitive logic is that it is based on the support relation over information states (or simply states), instead of the usual satisfaction relation over possible worlds widely used in various classical and non-classical logics. As a logic, $\text{InqB}$ collects all the valid propositional formulas supported by all the states. Intuitively, to a modal logician, a state in (propositional) inquisitive semantics is simply a set of possible worlds. To an epistemic logician, a state can be further viewed as an epistemic (55) Kripke model, where the agent is not sure which possible world is the actual one. It is very natural to ask whether there is an intrinsic connection between epistemic logic and inquisitive logic, given both are defined over similar models. In fact, there is a syntactic translation from inquisitive logic to modal and epistemic logic (e.g., [6], Section 5.4). In this paper, we focus on whether we can have an intuitive epistemic interpretation semantically.

Our approach is based on the non-classical view of inquisitive logic. Thanks to the intimate connection between inquisitive logic and Medvedev logic that we mentioned, we can make use of a crucial observation about the epistemic interpretation of intuitionistic and intermediate logics. Inspired by the original finite-problem semantics of Medvedev logic [22], Wang [37] proposed to interpret intuitionistic truth of a formula $\alpha$ as knowing how to prove/solve $\alpha$. Similar informal ideas of understanding intuitionistic truth as knowledge-how appeared a few times in the literature of intuitionistic logic in the past century (cf. e.g., [23]), starting from the very first paper by Heyting explaining the intuitive meaning of intuitionistic statements [16]:

To satisfy the intuitionistic demands, the statement must be the realisation of the expectation expressed by the proposition $p$. Here, then, is the Brouwerian statement of $p$:

It is known how to prove $p$.

In contrast with the previous informal philosophical discussions, we now have a formal way to capture this interpretation of intuitionistic truth not merely conceptually but also mathematically, based on the techniques for epistemic logics of know-wh proposed and studied by Wang (cf. e.g., [36, 34]). The main idea is to introduce the so-call bundled modalities, which pack a quantifier and an epistemic modality together to formalize the de re knowledge expressed by knowing how/why/what and so on (cf. e.g., [35, 39]). For example, knowing how to prove $\alpha$ (written as $K\alpha$) can be rendered as there exists a proof $\rho$ such that it is known that $\rho$ proves $\alpha$.

Combining this technique with some formalized BHK-interpretation of intuitionistic logic may allow us to turn intuitionistic logic and various intermediate logics into epistemic logics of knowing how. The general method is to use a powerful epistemic language based on classical logic to unload the implicit epistemic content hidden behind the propositional language of propositional intuitionistic logic, foreseen by Hintikka and van Benthem viewing intuitionistic logic as an implicit epistemic logic [18, 30]. An intuitionistic logic formula $\alpha$ is first translated into a know-how formula $K\alpha$ in our setting; then, depending on the structure of $\alpha$ and the BHK-interpretation, we can further “decode” $\alpha$ by reducing its complexity within the logical language, e.g., $K\alpha(\alpha \vee \beta)$ can be decomposed to $(K\alpha \vee K\beta)$, where the connectives outside the scope of $K\alpha$ are classical. This also helps us to understand the distinct role of the negation as the bridge between the classical and the intuitionistic settings. Such an epistemic approach can make intuitionistic logic and its relatives more intuitive, and the existing important technical results become more transparent.

In this paper, we apply such ideas to propositional inquisitive logic as a variant of intuitionistic logic under the non-classical view mentioned above. Note that the intended interpretation of inquisitive logic does not make reference to knowledge, thus what we are proposing is an alternative epistemic interpretation. Instead of talking about proofs and solutions in intuitionistic logic, here we are concerned with resolutions of issues raised by inquisitive formulas. Roughly speaking, a formula can be true in various ways, e.g., $\alpha \vee \beta$ can be true because of the truth of $\alpha$ or the truth of $\beta$. We say it is resolved if it is settled with a particular way of being true. In a nutshell, we interpret “$s$ supports $\alpha$” in inquisitive semantics as “knowing how to resolve $\alpha$” (or simply “knowing

\footnote{It is interesting to note that information states in game theory are precisely those epistemically indistinguishable possible worlds.}
how $\alpha$ is true”) over the epistemic model corresponding to $s$. For example, “$s$ supports $\alpha \lor \beta$” becomes “knowing how $\alpha \lor \beta$ is true” over the corresponding epistemic model. This interpretation is also extended to the entailment relation, i.e., $\alpha$ entails $\beta$ in inquisitive logic is interpreted as knowing how $\alpha$ is true entails knowing how $\beta$ is true, thus interpreting the reasoning in inquisitive logic as know-how preserving. This can be considered as the analog of correspondence of entailment in propositional logic and the standard epistemic logic of knowing that.

Actually, the idea of interpreting inquisitive formulas in terms of knowing how first appeared in Ciardelli’s master thesis in the early days of inquisitive logic [4]. In [12], the authors also made it more precise by using a notion of realization (or, say, resolution) inspired by the BHK-interpretation of intuitionistic logic, to which we will come back in Section 6 with detailed discussions.

Technically, compared to intuitionistic logic, there is a crucial simplification in inquisitive logic that each atomic proposition $p$ has one and only one possible resolution $p$. This is due to the assumption in inquisitive semantics that atomic propositions stand for statements, and questions are formed only via question-forming operators like the inquisitive disjunction (cf. [6, Section 2.5.5]). Translated into our epistemic interpretation, this assumes that you always know how to resolve an atomic formula if you know that it is true. On the other hand, knowing that $p$ is true is a presupposition of knowing how it is true. Therefore, knowing how to resolve the atomic proposition $p$ is equivalent to knowing that $p$ is resolvable in our epistemic rendering of inquisitive logic. Note that this cannot be extended to an arbitrary formula $\alpha$, which would trivialize the know-how formulas. Nevertheless, as we will see later, this simplification leads to the characteristic features (and the charm) of inquisitive logic. Based on this assumption about atomic propositions, we will eventually be able to eliminate the knowing how operator in our “epistemicization” of the inquisitive logic. All these will become more clear, after establishing our technical framework.

Here we summarize our main contributions in this paper:

- From an epistemic point of view, we propose a dynamic-epistemic logical framework of knowing how to give an alternative interpretation of inquisitive logic.
- We show that the propositional inquisitive logic, as a weak intermediate logic, is exactly the valid know-how fragment of our logic.
- We obtain a complete axiomatization of the full dynamic epistemic logic with intuitive axioms, which can transparently explain the axioms and results of inquisitive logic from our epistemic perspective.
- We show that both the knowing how modality and the dynamic modality can be eliminated in terms of expressivity, and thus inquisitive logic can be viewed as a fragment of epistemic logic.

More conceptually, with our approach, we want to bridge:

- **possible worlds and states** by viewing states as epistemic models to base our semantics on.
- **classical and non-classical logics** by using a modal logic based on classical connectives to interpret the non-classical inquisitive logic.
- **non-modal and modal formulations** by using the epistemic language of knowing how to reveal the rich dynamic-epistemic information behind the propositional formulas of inquisitive logic.
- **de re and de dicto knowledge** by connecting the knowledge-how with knowledge-that relevant to inquisitive reasoning.

We hope this epistemic approach can further enhance the power of inquisitive logic to wider applications while keeping its spirit. This may make inquisitive logic more intuitive to an audience who are not familiar with non-classical logics and support-based semantics. Future directions are discussed in Section 7.
Structure of the paper We recall the language and semantics of propositional inquisitive logic in Section 2. Section 3 introduces the language and semantics of our dynamic epistemic logic of knowing how, and shows that it captures the original inquisitive logic precisely as a fragment. In Section 4 we obtain an intuitive axiomatization for the full language and show its completeness by using the reduction axioms. Section 5 looks at the core concepts in inquisitive semantics from our intuitive epistemic perspective. In Section 6 we discuss the related work, particularly about inquisitive modal logic. We conclude in Section 7 with future directions.

2 Preliminaries: Inquisitive Logic

We first present some basic definitions and results of (propositional) inquisitive logic \textbf{InqB} following the expositions of [12, 6].

Definition 1 (Language PL) Given a countable set \( P \) of proposition letters, the language of propositional logic (\( \text{PL}^P \)) is defined as follows:

\[
\alpha ::= p \mid \bot \mid (\alpha \land \alpha) \mid (\alpha \lor \alpha) \mid (\alpha \rightarrow \alpha)
\]

where \( p \in P \). For abbreviations, we write \( \neg \alpha \) for \( \alpha \rightarrow \bot \), \( \top \) for \( \neg \bot \), and \( \alpha \leftrightarrow \beta \) for \( (\alpha \rightarrow \beta) \land (\beta \rightarrow \alpha) \).

\( P \) is assumed to be countable as in [6]. We write \( \text{PL}^P \) for \( \text{PL}^P \) when \( P \) is given in the context. For readability, in the rest of the paper, we often omit the parentheses if no ambiguity arises.

Instead of the satisfaction relation based on possible worlds, \textbf{InqB} adopts the following support relation in its semantics based on states, which makes \textbf{InqB} behave non-classically.

While the states were initially defined via the concept of index [3], it was later defined as a subset of the world set of a (propositional) information model in the recent literature (cf. e.g., [6]), here we adopt the latter definition.

Definition 2 (Information model) Given \( P \), an (information) model is a pair \( M = (W, V) \) where:

- \( W \) is a non-empty set of possible worlds;
- \( V : W \rightarrow \wp(P) \) is a valuation function.

Given \( M \), we refer to its components by \( W_M \) and \( V_M \). A full model is a model such that \( V[W] = \wp(P) \).

Following [12], the inquisitive semantics of \textbf{PL} over information models is given by the support relation.

Definition 3 (Support) Given \( P \) and an information model \( M = (W, V) \), an (information) state \( s \subseteq W \) is a subset of \( W \). \( W \) and \( \emptyset \) are called trivial state and inconsistent state respectively. Support is a relation between states and formulas (written as \( M, s \models \alpha \)):

1. \( M, s \models p \iff \forall w \in s, p \in w \).
2. \( M, s \models \bot \iff s = \emptyset \).
3. \( M, s \models (\alpha \land \beta) \iff M, s \models \alpha \) and \( M, s \models \beta \).
4. \( M, s \models (\alpha \lor \beta) \iff M, s \models \alpha \) or \( M, s \models \beta \).
5. \( M, s \models (\alpha \rightarrow \beta) \iff \forall t \subseteq s : \text{if } M, t \models \alpha \text{ then } M, t \models \beta \).

We write \( s \models \alpha \) for \( M, s \models \alpha \) when no confusion arises.

\footnote{Note that in contrast with [6], we do not allow \( W \) to be empty in order to ease the later presentation without changing any technical result.}
Definition 4 (Entailment ($\models$)) A set of PL-formulas $\Gamma$ entails a PL-formula $\alpha$ in inquisitive semantics, $\Gamma \models \alpha$, if and only if for any state $s$ in any model $M$ if $M, s \models \Gamma$ then $M, s \models \alpha$. We say $\alpha$ is valid if $\models \alpha$.

Definition 5 (Inquisitive logic) Inquisitive logic, $\text{InqB}$, is the set of PL-formulas that are valid in inquisitive semantics, i.e., the set of formulas that are supported by all states in all models.

It is straightforward to show:

Proposition 6 ([12]) For any PL-formula $\alpha$, $\alpha \in \text{InqB}$ iff for any full model $M$, $M, W_M \models \alpha$.

Now we present the proof system $\text{SINTDN}$ and two axioms schemata $\text{KP}$ and $\text{ND}_k$, which in combination give rise to two distinct axiomatizations of $\text{InqB}$.

System $\text{SINTDN}$

| Axioms       | Rules:       |
|--------------|--------------|
| $\text{INTU}$ | $\text{MP} \quad \alpha, \alpha \rightarrow \beta \quad \beta$ |
| $\text{DNp}$ | $\neg

Let $\text{KP}$ and $\text{ND}_k$ be the following axiom schemata:

$\text{KP} \quad (\neg \alpha \rightarrow \beta \lor \gamma) \rightarrow (\neg \alpha \rightarrow \beta) \lor (\neg \alpha \rightarrow \gamma)$

$\text{ND}_k \quad (\neg \alpha \rightarrow \bigwedge_{1 \leq i \leq k} \neg \beta_i) \rightarrow \bigwedge_{1 \leq i \leq k} (\neg \alpha \rightarrow \neg \beta_i)$

Theorem 7 (Axiomatizations of $\text{InqB}$ ([12])) $\text{SINTDN + KP}$ and $\text{SINTDN + \{ND}_k \mid k \in \mathbb{N}\}$ are both sound and complete for $\text{InqB}$.

The following definitions are taken from [12] adapted with a given model $M$ as in [6]. These characterize some important concepts in inquisitive semantics. Note that in the earlier literature (c.f.[12]), the definition of proposition was the set of alternatives. But the latest definition in [8] has been modified as the downward closure of the old one. We adopt the latest definition.

Definition 8 (Alternatives and propositions) Let $\alpha$ be a PL formula and let $M$ be a model.

- An alternative for $\alpha$ in $M$ is a maximal state $s$ in $M$ supporting $\alpha$;
- The proposition expressed by $\alpha$ in $M$ (call it $[\alpha]_M$), is the set of states in $M$ that supports $\alpha$. That is, $[\alpha]_M = \{ s \in W_M \mid s \models \alpha \}$.

Definition 9 (Inquisitiveness and informativeness) Let $\alpha$ be a PL formula and let $M$ be a model.

- $\alpha$ is inquisitive in $M$ if $[\alpha]_M$ contains at least two alternatives;
- $\alpha$ is informative in $M$ if there is some world in $M$ that is not included in any alternative for $\alpha$ in $M$.

Furthermore, we can define the relative notions of statements and questions.

Definition 10 (Questions and statements) Given a model $M$:

- $\alpha$ is a question in $M$ iff it is not informative in $M$;
- $\alpha$ is a statement in $M$ iff it is not inquisitive in $M$.

We will come back to these in Section[5] from our epistemic perspective. Before that, we shall introduce our framework of the logic of knowing how to interpret inquisitive logic epistemically.

3Following the new notion in [6], we call possibilities (Definition 2.9 in [12]) as alternatives, and call assertions (Definition 2.14 in [12]) as statements. Note that in Definition 2.14 in [12], questions and statements (assertions) are defined absolutely with respect to a full model with the trivial state. Here we generalized it to a relative notion as in the cases of inquisitiveness and informativeness.
3 Inquisitive logic as a logic of knowing how

In this section, we give a formal epistemic interpretation of inquisitive logic by using an epistemic logic of knowing how.

3.1 Language and models

We first introduce our dynamic epistemic language of knowing how, where on top of PL we add three modalities of know-that, know-how, and updates.

**Definition 11 (Language DELKh)** Given a countable set of proposition letters P, the Dynamic Epistemic Language of Knowing How (DELKh) is defined as follows:

\[ \varphi ::= p \mid \bot \mid (\varphi \land \varphi) \mid (\varphi \lor \varphi) \mid (\varphi \rightarrow \varphi) \mid K\varphi \mid K\alpha \mid \Box\varphi \]

where \( p \in P \) and \( \alpha \in PL^P \). For abbreviations, we write \( \hat{K} \) for \( \neg K\neg \), \( \hat{K}\alpha \) for \( \neg K\neg \alpha \) and write \( \diamond \) for \( \neg \Box \). We denote the \( K\)-free fragment as DELKh, and the \( \Box\)-free fragment of DELKh as ELKhd.

Again, we often omit the P from DELKh when P is fixed in the context. Intuitively, \( K\varphi \) expresses that “the agent knows that \( \varphi \)”, \( K\alpha \) says that “the agent knows how to resolve \( \alpha \)” or simply “the agent knows how \( \alpha \) is true”, and \( \Box\varphi \) says that “\( \varphi \) holds, no matter what further information is given”. Note that \( K\alpha \) only takes PL-formulas \( \alpha \) whereas K and \( \Box \) can be combined with any DELKh-formulas \( \varphi \). Therefore we can express \( K\neg K\alpha \) but not \( K\Box K\alpha \) in DELKh.

DELKh will be interpreted on standard single-agent epistemic models where the (implicit) epistemic relation is the total relation. Technically speaking, such models are exactly the information models as we defined in Definition 2 when we omit the epistemic relation since it is always total. For this reason in the paper, we will also call information models epistemic models.

For notational convenience, we also write \( w \in M \) in case that \( w \in W_M, M' \subseteq M \) in case that \( M' \) is a submodel of \( M \). If \( w \in M' \subseteq M \) then we write \( (M', w) \subseteq (M, w) \).

Although the models are simply S5 epistemic models, in order to reflect the non-classical features of InqB, we define the semantics for \( K\alpha \) via the resolutions, based on the idea that knowing how \( \alpha \) is true means knowing a particular resolution for \( \alpha \), in line with the BHK-interpretation of the intuitionistic connectives. We first define the resolution space for each formula below in Definition 12. The actual resolutions on each world for each formula, to be defined in Definition 14 will be subsets of the resolution space.

**Definition 12 (Resolution space)** \( S \) is a function assigning each \( \alpha \) its set of potential resolutions:

\[
S(p) = \{p\}, \text{ for } p \in P
\]
\[
S(\bot) = \{\bot\}
\]
\[
S(\alpha \lor \beta) = (S(\alpha) \times \{0\}) \cup (S(\beta) \times \{1\})
\]
\[
S(\alpha \land \beta) = S(\alpha) \times S(\beta)
\]
\[
S(\alpha \rightarrow \beta) = S(\beta)^{S(\alpha)}
\]

Let \( S = \bigcup_{\alpha \in PL} S(\alpha) \).

Our definition is similar to the definition of realizations in [25, Part 4], which was proposed not in the context of inquisitive logic. The definition of resolution space reflects the intuition that for each \( \alpha_i \), there is a set of possible ways to resolve it as an issue or say to make it true. Intuitively, the set of potential resolutions of a disjunction is the disjoint union of the potential resolutions of each disjunct: to make a disjunction true you need to explicitly make one of the disjuncts true. The

^[4] Nevertheless, in a multi-agent setting, explicit epistemic relations are necessary. We leave it for a future occasion.
resolution space of a conjunction is the Cartesian product of the resolution space of each conjunct: to make a conjunction true, you need to make both conjuncts true. The resolution space for an implication, is the set of functions from the resolution of the antecedent to the resolution space of the consequent: to make an implication true, you need to have a way to transform any resolution of the antecedent to some resolution of the consequent.

Note that the potential resolutions for atomic propositions are assumed to be singletons, which reflects the underlying assumption in inquisitive semantics that atomic propositions do not bring inquisitiveness themselves. In other words, we always know how to resolve atomic propositions when possible. This is the most fundamental difference between InqB and other intermediate logics such as Medvedev logic. It will become more clear when we discuss the axioms later.

Technically speaking, the possible resolution of each atomic proposition is non-empty and finite: it cannot be empty or a fixed singleton set independent from the BHK-interpretation. We call this the resolution space for each atomic proposition.

For technical convenience, in the line of the resolution space for atomic propositions, the resolution space of each atomic proposition is defined as

\[
\{ \alpha \in \mathcal{P} \mid \exists f \in \{ \bot \} | f[R(w, \alpha)] \subseteq R(w, \alpha) \}
\]

and it is finite.

Now given a model, we can generate the actual resolutions of each atomic proposition on each world.

**Definition (Resolution)** Given a model \( \mathcal{M} \), the resolution function \( R : W \times \mathcal{P} \rightarrow S \) is defined as follows:

\[
R(w, \bot) = \emptyset
\]

\[
R(w, p) = \begin{cases} \{p\} & \text{if } p \in V_{\mathcal{M}}(w) \\ \emptyset & \text{otherwise} \end{cases}
\]

\[
R(w, \alpha \lor \beta) = (R(w, \alpha) \times \{0\}) \cup (R(w, \beta) \times \{1\})
\]

\[
R(w, \alpha \land \beta) = R(w, \alpha) \times R(w, \beta)
\]

\[
R(w, \alpha \rightarrow \beta) = \{ f \in S(\beta)^{S(\alpha)} \mid f[R(w, \alpha)] \subseteq R(w, \beta) \}
\]

For \( U \subseteq W \), we write \( R(U, \alpha) \) for \( \bigcap_{w \in U} R(w, \alpha) \). When \( U = W_{\mathcal{M}} \) we also write \( R(\mathcal{M}, \alpha) \) for \( R(U, \alpha) \).

We call \( R(w, \alpha) \) the set of resolutions for an issue \( \alpha \) on a given world \( w \). It is clear that \( R(w, \alpha) \subseteq S(\alpha) \).

Note that although the resolution space of \( \bot \) is non-empty for technical convenience, it cannot be empty or a fixed singleton set independent from the BHK-interpretation. An atomic proposition \( p \) can have the resolution \( p \) only when it is true on \( w \). The resolutions for an implication \( \alpha \rightarrow \beta \) on a possible world are the functions in the resolution space of \( \alpha \rightarrow \beta \) mapping a resolution of \( \alpha \) to a resolution of \( \beta \) on the same world in line with the BHK-interpretation.

Recall that \( \neg \alpha \) is the abbreviation of \( \alpha \rightarrow \bot \). Since negation plays an important role in intermediate logics, we have the following observation, which is useful for later discussions.

**Proposition 15** For any \( \mathcal{M}, w, \alpha \), \( R(w, \neg \alpha) \) is either \( \emptyset \) or a fixed singleton set independent from \( w \), and \( R(w, \neg \alpha) = \emptyset \) iff \( R(w, \alpha) \neq \emptyset \).

**Proof** By the definitions of \( R \) and \( S \):

\[
R(w, \alpha \rightarrow \bot) = \{ f \in S(\bot)^{S(\alpha)} \mid f[R(w, \alpha)] \subseteq R(w, \bot) \}\]

\[
= \{ f \in \{ \bot \}^{S(\alpha)} \mid f[R(w, \alpha)] \subseteq \emptyset \}\]

\[
= \{ f \in \{ \bot \}^{S(\alpha)} \mid f[R(w, \alpha)] = \emptyset \}\]

\[
= \begin{cases} \emptyset & \text{if } R(w, \alpha) \neq \emptyset \\ \{ f^+_w \} & \text{if } R(w, \alpha) = \emptyset \end{cases}
\]
where \( f_\perp^\alpha \) is the constant function such that \( f_\perp^\alpha(x) = \bot \) for any \( x \in S(\alpha) \). Note that \( f_\perp^\alpha \) only depends on \( \alpha \) and it is independent from \( w \). 

It is also important that \( R(w, \alpha) \) only depends on the valuation on \( w \) itself but not on other worlds.

**Proposition 16** For any \( M, w \) and \( N, v \), if \( V_\mathcal{M}(w) = V_\mathcal{N}(v) \) then \( R(w, \alpha) = R(v, \alpha) \) for all \( \alpha \in \mathcal{PL} \).

### 3.2 Semantics

Given the definition of resolutions, we can define the satisfaction relation of \( \text{DELKh} \) on possible worlds in epistemic models. Note that the connectives outside the scope of \( \mathcal{K} \) are classical and the semantics of \( K \) is standard as in epistemic logic. The semantics of \( \mathcal{K}_\alpha \) on a world \( w \) is the formalization of the idea that the agent knows how to resolve \( \alpha \) iff it knows a particular resolution of \( \alpha \). The semantics of the dynamic modality \( \Box \) is based on taking submodels as in a version of arbitrary announcement logic [1], representing informational updates in terms of eliminating possibilities.

**Definition 17 (Semantics)** For any \( \varphi \in \text{DELKh} \) and a pointed model \( M, w \) where \( M = \langle W, V \rangle \), the satisfaction relation is defined as below:

\[
\begin{align*}
\mathcal{M}, w \not\models \bot & \iff p \in V(w) \\
\mathcal{M}, w \models \varphi & \iff \mathcal{M}, w \models \varphi \\
\mathcal{M}, w \models (\varphi \lor \psi) & \iff \mathcal{M}, w \models \varphi \text{ or } \mathcal{M}, w \models \psi \\
\mathcal{M}, w \models (\varphi \land \psi) & \iff \mathcal{M}, w \models \varphi \text{ and } \mathcal{M}, w \models \psi \\
\mathcal{M}, w \models (\varphi \rightarrow \psi) & \iff \mathcal{M}, w \models \varphi \text{ implies } \mathcal{M}, w \models \psi \\
\mathcal{M}, w \models \Box \varphi & \iff \text{for any } (M', w) \subseteq (M, w), \mathcal{M}', w \models \varphi \\
\mathcal{M}, w \models \mathcal{K} \varphi & \iff \text{for any } v \in M, \mathcal{M}, v \models \varphi \\
\mathcal{M}, w \models \mathcal{K}_\alpha & \iff \text{there exists } x \in S(\alpha) \text{ s.t. for any } v \in M, x \in R(v, \alpha)
\end{align*}
\]

We say a formula is valid on \( M \) (\( M \models \varphi \)) if \( M, w \models \varphi \) for all \( w \in M \). We say a set of \( \text{DELKh} \)-formula \( \Gamma \) entails another formula \( \varphi \) (\( \Gamma \models \varphi \)), if for any pointed model \( M, w, M, w \models \Gamma \) implies \( M, w \models \varphi \). We say \( \varphi \) is valid (\( \models \varphi \)) if \( \Box \models \varphi \). A formula schema is valid if all its instances are valid.

It is not hard to see that the structure of the truth condition of \( \mathcal{K} \) is in terms of the bundle \( \exists \mathcal{K} \mathcal{A} \) as in other know-wh logics [35, 34]. Recall that \( R(M, \alpha) = (\bigcap_{v \in M} R(v, \alpha)) \) (cf. Definition [14]). The semantics of \( \mathcal{K} \) can be then reformulated as below for notational brevity.

\[
\mathcal{M}, w \models \mathcal{K}_\alpha \iff R(M, \alpha) \neq \emptyset
\]

Note that the truth conditions of \( K \) and \( \mathcal{K} \) do not depend on the designated world, therefore we have:

**Proposition 18** For any model \( M, w \):

- \( M, w \models \mathcal{K}_\alpha \iff M \models \mathcal{K}_\alpha \text{ and } M, w \models \neg \mathcal{K}_\alpha \iff M \models \neg \mathcal{K}_\alpha \);
- \( M, w \models K_\alpha \iff M \models K_\alpha \text{ and } M, w \models \neg K_\alpha \iff M \models \neg K_\alpha \).

As a consequence, the introspection axioms \( \mathcal{K}_\alpha \rightarrow K \mathcal{K}_\alpha \) and \( \neg \mathcal{K}_\alpha \leftrightarrow K \neg \mathcal{K}_\alpha \) are valid.

It is clear that the above semantics is simply classical for \( \alpha \in \mathcal{PL} \). In particular, \( \{ \alpha \in \mathcal{PL} \mid \models \alpha \} \) is classical propositional logic (CPL). However, let \( \text{InqKhL} \) be \( \{ \alpha \mid \models \mathcal{K}_\alpha \} \subseteq \mathcal{PL} \), we will show that \( \text{InqKhL} = \text{InqB} \). Before that, to understand the semantics of \( \mathcal{K} \) better, we first show that the classical semantics of \( \alpha \) can be viewed from the perspective of resolutions: resolvability equals truth. Note that for atomic formulas \( p, M, w \models p \iff R(w, p) \neq \emptyset \) is obviously true, however we need to generalize it to any formula \( \alpha \in \mathcal{PL} \).
Proposition 19. For any $\alpha \in \text{PL}$ and pointed model $M, w. M, w \models \alpha \iff R(w, \alpha) \neq \emptyset$, where $\alpha \in \text{PL}$.

Proof. Induction on the structure of $\alpha$:

$M, w \models p \iff p \in V_M(w) \iff R(w, p) = \{p\} \iff R(w, p) \neq \emptyset$

$M, w \not\models \bot \iff R(w, \bot) = \emptyset$

$M, w \models (\alpha \land \beta) \iff M, w \models \alpha$ or $M, w \models \beta \iff R(w, \alpha) \neq \emptyset$ or $R(w, \beta) \neq \emptyset$

$M, w \models \alpha \rightarrow \beta \iff M, w \models \alpha$ implies $M, w \models \beta \iff R(w, \alpha) \neq \emptyset$ implies $R(w, \beta) \neq \emptyset$

$S(\beta)^{S(\alpha)} \neq \emptyset$ and $f[R(w, \alpha)] \subseteq R(w, \beta)$ is possible

$R(w, \alpha \rightarrow \beta) \neq \emptyset$

For negations, based on Propositions 19 and 15, we have

$M, w \models \lnot \alpha \iff R(w, \alpha) = \emptyset \iff M, w \not\models \alpha$.

Now, based on Proposition 19 we have an alternative semantics for $K\alpha$ for $\alpha \in \text{PL}$:

$M, w \models K\alpha \iff$ for any $v \in M$, there exists an $x \in R(v, \alpha)$

Compared with the truth condition of $K\alpha$, it now becomes clear that the distinction between $K\alpha$ and $K$ is exactly the distinction between the de re and de dicto knowledge, i.e., knowing $\alpha$ is resolvable vs. knowing how $\alpha$ is resolved.

$M, w \models K\alpha \iff$ there exists an $x$ s.t. for any $v \in M$, $x \in R(v, \alpha)$

Based on this distinction, $K\alpha$ is clearly stronger than $K\alpha$:

Proposition 20. $K\alpha \rightarrow K\alpha$ is valid for all $\alpha \in \text{PL}$.

The distinction disappears if we consider the atomic propositions since there can be at most one fixed resolution for each $p \in \text{PL}$.

Proposition 21. $Kp \leftrightarrow Kp$ is valid for all $p \in \text{P}$.

However, $K\alpha \rightarrow K\alpha$ does not hold in general.

Example 1. $K(p \lor \lnot p) \rightarrow K(p \lor \lnot p)$ is not valid, e.g., in the model $(\{w, v\}, V)$ where $p \in V(w)$ but $p \not\in V(v)$, $K(p \lor \lnot p)$ holds everywhere but $K(p \lor \lnot p)$ holds nowhere.

The example also shows that the valid $K$-formulas are not closed under uniform substitution, to which we will come back in Section 4.

It is well-known that in intermediate logics negation plays a role in bridging the classical and the intuitionistic validities, we show that this can be understood by the fact that $\lnot$ bridges $K\alpha$ and $K$ in our setting.

Proposition 22 (Negative translation). $K\lnot \alpha \leftrightarrow K\lnot \alpha$ is valid. As a consequence, $K\lnot \alpha \leftrightarrow K\alpha$ is valid.
Now we have an intuitive reading of reduction axioms. The reduction formally in Section 4 when discussing the axiomatization featuring the corresponding Remark 1.

Thus \( M, w \models \lnot \alpha \iff R(M, \alpha) \neq \emptyset \iff R(v, \alpha) = \emptyset \).

Therefore \( M, w \models \lnot \alpha \iff M, w \models K\alpha \).

Although we cannot reduce \( \mathsf{K}\alpha \) to \( \mathsf{K} \) in general, we can reduce the complexity of \( \alpha \) in \( \mathsf{K}\alpha \) step by step, which will play an important role in the later sections.

**Proposition 23** The following formulas and schemata are valid:

- \( \mathsf{K}\perp \iff \perp \)
- \( \mathsf{K}(\alpha \lor \beta) \iff \mathsf{K}\alpha \lor \mathsf{K}\beta \)
- \( \mathsf{K}(\alpha \land \beta) \iff \mathsf{K}\alpha \land \mathsf{K}\beta \)
- \( \mathsf{K}(\alpha \rightarrow \beta) \iff \mathsf{K}\square(\mathsf{K}\alpha \rightarrow \mathsf{K}\beta) \)

**Proof** We only show the non-trivial cases of \( \mathsf{K}(\alpha \lor \beta) \) and \( \mathsf{K}(\alpha \rightarrow \beta) \).

- \( M, w \models \mathsf{K}(\alpha \lor \beta) \iff R(M, \alpha \lor \beta) \neq \emptyset \)

  \[ \iff \text{ there exists an } (x, 0) \in R(M, \alpha \lor \beta) \text{ or there exists a } (y, 1) \in R(M, \alpha \lor \beta) \]

- \( \iff \text{ there exists an } x \in R(M, \alpha) \text{ or there exists a } y \in R(M, \beta) \)

- \( \iff M, w \models \mathsf{K}\alpha \text{ or } M, w \models \mathsf{K}\beta \iff M, w \models \mathsf{K}\alpha \lor \mathsf{K}\beta \)

- \( \mathsf{K}(\alpha \rightarrow \beta) \iff \mathsf{K}\square(\mathsf{K}\alpha \rightarrow \mathsf{K}\beta) \)

\( \iff : \) Suppose \( M, w \models \mathsf{K}\square(\mathsf{K}\alpha \rightarrow \mathsf{K}\beta) \), then by the semantics, there is some \( f \in R(M, \alpha \rightarrow \beta) \).

Towards a contradiction, suppose \( \mathcal{M}, w \not\models K\square(\mathsf{K}\alpha \rightarrow \mathsf{K}\beta) \). That is, there is an \( v \in \mathcal{M} \) and an \( \mathcal{M}', v \subseteq \mathcal{M} \), s.t. \( \mathcal{M}', v \models \mathsf{K}\alpha \) but \( \mathcal{M}', v \not\models \mathsf{K}\beta \). So there is an \( x \in R(\mathcal{M}', \alpha) \). Recall that \( f \) is a function with domain \( S(\alpha) \), and \( S(\alpha) \supseteq R(u, \alpha) \) for all \( u \in \mathcal{M}' \), thus \( x \in \mathcal{D}(f) \).

Moreover, since \( f \in R(\mathcal{M}, \alpha \rightarrow \beta) \), \( f \in R(\mathcal{M}', \alpha \rightarrow \beta) \). Let \( y = f(x) \). By the definition of \( R(\mathcal{M}', \alpha \rightarrow \beta) \), \( y \in R(u, \beta) \) for each \( u \in \mathcal{M}' \). Therefore \( \mathcal{M}', v \models \mathsf{K}\beta \), a contradiction.

\( \Leftarrow : \) Suppose \( \mathcal{M}, w \models \mathsf{K}\square(\mathsf{K}\alpha \rightarrow \mathsf{K}\beta) \), then for all \( v \in \mathcal{M}, \mathcal{M}, v \not\models \square(\mathsf{K}\alpha \rightarrow \mathsf{K}\beta) \). By the semantics of \( \square \), for any \( v \in \mathcal{M} \) and for any \( \mathcal{M}', v \subseteq \mathcal{M}, \mathcal{M}', v \not\models \mathsf{K}\alpha \rightarrow \mathsf{K}\beta \) \( (*) \). By Proposition 13, \( S(\alpha) \) is finite and non-empty, thus we can assume \( S(\alpha) = \{x_0, x_1, \ldots, x_n\} \) for some \( n \in \mathbb{N} \). For \( i \in \{0, \ldots, n\} \), let \( \mathcal{M}_i = \{ w \mid x_i \in R(w, \alpha) \} \). If \( \mathcal{M}_i \) is not empty then let \( \mathcal{M}_1 \) be the submodel of \( \mathcal{M} \) such that \( W_{\mathcal{M}_1} = W_{\mathcal{M}_1} \). Clearly \( x_i \in R(W_{\mathcal{M}_1}, \alpha) \), therefore for any \( u \in \mathcal{M}_1, \mathcal{M}_1, u \models \mathsf{K}\alpha \). By \( (*) \) we have \( \mathcal{M}_1, u \not\models \mathsf{K}\beta \) thus there is a \( y_i \in R(W_i, \beta) \).

Now fix a \( y \in S(\beta) \neq \emptyset \), let \( f = \{ (x_i, y_i) \mid i \in \{0, \ldots, n\} \} \) and \( W_i \not= \emptyset \) \( \cup \{ (x_i, y) \mid i \in \{0, \ldots, n\} \} \) and \( W_i = \emptyset \). Clearly \( f \in S(\beta)S(\alpha) \). Now for any \( v \in \mathcal{M} \) and \( i \in \{0, \ldots, n\} \), if \( x_i \in R(v, \alpha) \) then \( v \in W_i \) by the definition of \( W_i \), thus \( y_i \in R(v, \beta) \) by the construction of \( f \). Therefore \( \mathcal{M}, v \models \mathsf{K}(\alpha \rightarrow \beta) \) for all \( v \in \mathcal{M} \). It follows that \( \mathcal{M}, v \not\models \mathsf{K}(\alpha \rightarrow \beta) \) for all \( v \in \mathcal{M} \) including \( w \). Note that the axiom of choice is not needed in the above finitary constructions.

**Remark 1** Propositions 21 and 23 will help us to eliminate the \( \mathsf{K} \) modalities without changing the expressive power. Actually, we can also eliminate the \( \square \) modality eventually. We will discuss the reduction formally in Section 4 when discussing the axiomatization featuring the corresponding reduction axioms.

Now we have an intuitive reading of \( \alpha \lor \neg \alpha \) in inquisitive logic based on Propositions 23 and 22.

\[ \mathcal{M}, w \models \mathsf{K}(\alpha \lor \neg \alpha) \iff \mathcal{M}, w \models \mathsf{K}\alpha \lor \mathsf{K}\neg \alpha \iff \mathcal{M}, w \models \mathsf{K}\alpha \lor \mathsf{K}\neg \alpha \]
The formula $\mathcal{K}\alpha \lor \mathcal{K}\neg\alpha$ says either you know how to resolve $\alpha$ or you know it is not resolvable/true, and it is clearly not valid in general. This explains intuitively why inquisitive logic does not accept the law of excluded middle.

Given the validity of $\mathcal{K}(\alpha \rightarrow \beta) \leftrightarrow \mathcal{K}\Box(\mathcal{K}\alpha \rightarrow \mathcal{K}\beta)$ and Proposition 18, we can give an alternative compositional truth condition to $\mathcal{K}(\alpha \rightarrow \beta)$, which is more handy to use.

**Proposition 24** For any model $\mathcal{M}$, $\mathcal{M}, w \models \mathcal{K}(\alpha \rightarrow \beta)$ iff for any $\mathcal{M}' \subseteq \mathcal{M}$, $\mathcal{M} \models \mathcal{K}\alpha$ implies $\mathcal{M} \models \mathcal{K}\beta$.

**Proof** It suffices to show that $\mathcal{M}, w \models \mathcal{K}\Box(\mathcal{K}\alpha \rightarrow \mathcal{K}\beta)$ iff for any $\mathcal{M}' \subseteq \mathcal{M}$, $\mathcal{M} \models \mathcal{K}\alpha$ implies $\mathcal{M} \models \mathcal{K}\beta$, which follows directly from the semantics of $\mathcal{K}\Box$. Note that Given a pointed model $\mathcal{M}, w$, $\Box$ quantifies over all the submodels of $\mathcal{M}'$ such that $w \in \mathcal{M}'$. Since on an $S5$ model, $K$ refers to all the points $w \in \mathcal{M}$, the combination of $K\Box$ quantifies over all the submodels of $\mathcal{M}$. That is, for any $\mathcal{M}' \subseteq \mathcal{M}$ and $v \in \mathcal{M}', \mathcal{M}', v \models \mathcal{K}\alpha$ implies $\mathcal{M}', v \models \mathcal{K}\beta$. By Proposition 18 the proof is completed. 

In the following, given $\Gamma \subseteq \PL$, let $\mathcal{K}\Gamma = \{ \mathcal{K}\gamma \mid \gamma \in \Gamma \}$. As another consequence of the validity of $\mathcal{K}(\alpha \rightarrow \beta) \leftrightarrow \mathcal{K}\Box(\mathcal{K}\alpha \rightarrow \mathcal{K}\beta)$, we have:

**Proposition 25** $\mathcal{K}\Gamma \models \mathcal{K}(\alpha \rightarrow \beta)$ iff $\mathcal{K}\Gamma \models \mathcal{K}\alpha \rightarrow \mathcal{K}\beta$. As a special case, $\models \mathcal{K}(\alpha \rightarrow \beta)$ iff $\models \mathcal{K}\alpha \rightarrow \mathcal{K}\beta$.

**Proof** It suffices to show that $\mathcal{K}\Gamma \models \mathcal{K}\Box(\mathcal{K}\alpha \rightarrow \mathcal{K}\beta)$ iff $\mathcal{K}\Gamma \models \mathcal{K}\alpha \rightarrow \mathcal{K}\beta \iff$ is based on the fact that $\mathcal{K}\phi \rightarrow \phi$ and $\Box\phi \rightarrow \phi$ are valid. $\iff$ is based on the fact that if $\mathcal{M}, w \models \mathcal{K}\Gamma$ then any for submodel $\mathcal{M}'$ of $\mathcal{M}$, $\mathcal{M}' \models \mathcal{K}\Gamma$ by the semantics of $\mathcal{K}$. Indeed, if for all the worlds in $\mathcal{M}$, there exists a uniform resolution for each formula in $\Gamma$, the same resolutions will certainly serve as the uniform resolutions for worlds in $\mathcal{M}'$. Therefore, supposing $\mathcal{K}\Gamma \models \mathcal{K}\alpha \rightarrow \mathcal{K}\beta$ and $\mathcal{M}, w \models \mathcal{K}\Gamma$, it follows that $\mathcal{K}\alpha \rightarrow \mathcal{K}\beta$ is satisfied on all the submodels of $\mathcal{M}$. By Proposition 18 that is, for any $\mathcal{M}' \subseteq \mathcal{M}$, $\mathcal{M} \models \mathcal{K}\alpha$ implies $\mathcal{M} \models \mathcal{K}\beta$. By Proposition 24 we have $\mathcal{M}, w \models \mathcal{K}(\alpha \rightarrow \beta)$. 

Based on Proposition 25, we have the following theorem for $\mathcal{K}$ formulas, which is the counterpart of Proposition 3.10 (deduction theorem) in [12].

**Theorem 26** For any $\alpha \in \PL$ and $\Gamma, \Gamma' \subseteq \PL$ such that $\Gamma$ is finite,

$$
\mathcal{K}(\Gamma' \cup \Gamma) \models \mathcal{K}\alpha \iff \mathcal{K}\Gamma' \models \mathcal{K}\left( \bigwedge_{\gamma \in \Gamma} \gamma \rightarrow \alpha \right).
$$

**Proof**

$\mathcal{K}(\Gamma' \cup \Gamma) \models \mathcal{K}\alpha \iff$ for any $\mathcal{M}, w$ such that $\mathcal{M}, w \models \mathcal{K}\Gamma' \cup \mathcal{K}\Gamma$, then $\mathcal{M}, w \models \mathcal{K}\alpha$

$\iff$ for any $\mathcal{M}, w$ such that $\mathcal{M}, w \models \mathcal{K}\Gamma'$, if $\mathcal{M}, w \models \bigwedge_{\gamma \in \Gamma} \mathcal{K}\gamma$, then $\mathcal{M}, w \models \mathcal{K}\alpha$

$\iff$ for any $\mathcal{M}, w$ such that $\mathcal{M}, w \models \mathcal{K}\Gamma'$, $\mathcal{M}, w \models \bigwedge_{\gamma \in \Gamma} \mathcal{K}\alpha$

$\iff \mathcal{K}\Gamma' \models \bigwedge_{\gamma \in \Gamma} \mathcal{K}\gamma \rightarrow \mathcal{K}\alpha$

$\iff \mathcal{K}\Gamma' \models \mathcal{K}\left( \bigwedge_{\gamma \in \Gamma} \gamma \rightarrow \alpha \right)$ (by Proposition 23)

$\iff \mathcal{K}\Gamma' \models \mathcal{K}(( \bigwedge_{\gamma \in \Gamma} \gamma \rightarrow \alpha) \text{ (by Proposition 25)}}$

As an analog of the persistence of $\mathcal{K}\alpha$ in our setting with $\Box$. Intuitively, once we know how to resolve $\alpha$, we will not forget, even given more information.
Proposition 27 (Persistence) $\text{Kh} \alpha \leftrightarrow \Box \alpha$ is valid for any $\alpha \in \text{PL}$.

PROOF $\implies$: Suppose $\mathcal{M}, w \vDash \text{Kh} \alpha$ then $R(\mathcal{M}, \alpha) \neq \emptyset$. It is clear that $R(\mathcal{M}, \alpha) \subseteq R(\mathcal{M}', \alpha)$ for any submodel $\mathcal{M}'$. Therefore $R(\mathcal{M}', \alpha) \neq \emptyset$ for any submodel $\mathcal{M}'$, thus $\mathcal{M}, w \vDash \Box \alpha$.

$\impliedby$: It is trivial since a model is also a submodel of itself.

Another important interaction property between $\text{Kh}$ and $\Box$ is the following, which can be compared to Proposition 2.5 in [12] regarding the singleton state.

Proposition 28 $\alpha \leftrightarrow \Diamond \alpha$ is valid for any $\alpha \in \text{PL}$.

PROOF $\implies$: It is valid because we can always go to a singleton submodel containing the current world only, where $\text{Kh} \alpha$ holds. Note that for singleton models, i.e., models with only one world, $\text{Kh} \alpha \rightarrow \text{Kh} \alpha$ holds trivially for any $\alpha$ since any actual resolution on that single world will be the uniform resolution.

$\impliedby$ is based on the fact that the updates do not change the truth values of propositional formulas on the current world, and the validity of $\text{Kh} \alpha \rightarrow \text{Kh} \alpha$ and $\text{Kh} \alpha \rightarrow \alpha$.

As a feature distinguishing intuitionistic logic and classical logic, disjunction property is also an important property of inquisitive logic [12 Prop. 3.9]. It holds naturally in our logic.

Proposition 29 (Disjunction Property) For any formulas $\alpha, \beta \in \text{PL}$, $\vDash \text{Kh}(\alpha \lor \beta) \iff \vDash \text{Kh} \alpha$ or $\vDash \text{Kh} \beta$.

PROOF $\implies$: Suppose $\not\vDash \text{Kh} \alpha$ and $\not\vDash \text{Kh} \beta$, then we have some models $\mathcal{M}, w$ and $\mathcal{N}, v$ such that $\mathcal{M}, w \not\vDash \text{Kh} \alpha$ and $\mathcal{N}, v \not\vDash \text{Kh} \beta$. Now we can simply merge the two models together as the disjoint union $\mathcal{M} \uplus \mathcal{N}$. By the semantics of $\text{Kh}$ it is clear that $\mathcal{M} \uplus \mathcal{N}, w \not\vDash \text{Kh} \alpha \lor \text{Kh} \beta$. By Proposition 23 $\not\vDash \text{Kh}(\alpha \lor \beta)$.

$\impliedby$ is trivial by Proposition 22.

As some examples, we show the validity of $\text{Kh}$-versions of some axioms and valid formulas in InqB (cf. Theorem 7).

Proposition 30 The following are valid:

- $\text{KhD}p$ $\text{Kh}(\neg p \rightarrow p)$ for $p \in \text{P}$
- $\text{KhPEIRCEp}$ $\text{Kh}((p \rightarrow q) \rightarrow p)$ for $p, q \in \text{P}$
- $\text{KhKP}$ $\text{Kh}((\neg \alpha \rightarrow \beta \lor \gamma) \rightarrow (\neg \alpha \rightarrow \beta) \lor (\neg \alpha \rightarrow \gamma))$
- $\text{KhND}k$ $\text{Kh}((\neg \alpha \lor \bigvee _{1 \leq i \leq k} \neg \beta_i ) \lor \bigvee _{1 \leq i \leq k} (\neg \alpha \lor \neg \beta_i ) )$

PROOF For $\text{KhD}p$: by Proposition 25, it suffices to check $\vDash \text{Kh}(\neg p \rightarrow p \rightarrow p)$ which amounts to check $\vDash \text{Kh}(p \rightarrow p)$, which is valid by Proposition 21.

For $\text{KhPEIRCEp}$: by Proposition 25 it suffices to check $\vDash \text{Kh}((p \rightarrow q) \rightarrow p \rightarrow q)$ which amounts to $\vDash \Box(\text{Kh}(p \rightarrow q) \rightarrow \text{Kh}(p \rightarrow q))$. By Proposition 21 we need to check $\vDash \Box(\text{Kh}(p \rightarrow q) \rightarrow \text{Kh}(p \rightarrow q))$. Now suppose $\mathcal{M}, w \not\vDash \text{Kh}(p \rightarrow q)$ then there is $v \in \mathcal{M}$ such that $\mathcal{M}, v \not\vDash \neg p$. We need to show that $\mathcal{M}, w \not\vDash \text{Kh}(p \rightarrow q)$. Take the singleton submodel $\mathcal{M}'$ of $\mathcal{M}$ with the world $v$ only, then it is clear that $\mathcal{M}', v \not\vDash \text{Kh}(p \rightarrow q)$.

For $\text{KhKP}$: By Proposition 25 we only need to check $\vDash \text{Kh}(\neg \alpha \lor \beta \lor \gamma)$. It amounts to $\vDash \Box(\text{Kh}(\neg \alpha \lor (\text{Kh}(\beta \lor \text{Kh}(\gamma)))) \rightarrow \Box(\text{Kh}(\neg \alpha \lor \beta)) \lor \Box(\text{Kh}(\neg \alpha \lor \text{Kh}(\gamma)))$ based on Proposition 23. We prove its contraposition. Suppose $\mathcal{M}, w \not\vDash \Box(\text{Kh}(\neg \alpha \lor \beta)) \land \neg \Box(\text{Kh}(\neg \alpha \lor \text{Kh}(\gamma)))$ then there are two submodels $\mathcal{M}_1$ and $\mathcal{M}_2$ such that $\mathcal{M}_1 \not\vDash \text{Kh}(\neg \alpha \lor \beta)$ and $\mathcal{M}_2 \not\vDash \text{Kh}(\neg \alpha \lor \text{Kh}(\gamma))$. Then the union $\mathcal{M}_1 \cup \mathcal{M}_2$ is a submodel of $\mathcal{M}$ making $\text{Kh}(\neg \alpha \lor (\text{Kh}(\beta \lor \text{Kh}(\gamma)))$ false. Thus $\mathcal{M}, w \not\vDash \Box(\text{Kh}(\neg \alpha \lor (\text{Kh}(\beta \lor \text{Kh}(\gamma))))$.

The validity of $\text{KhND}k$ can be proved similarly as in the case of $\text{KhKP}$.
Note that Peirce’s schema \(\text{Kh}((\alpha \to \beta) \to \alpha)\) is not valid in general. For example, take the instance where \(\alpha = p \lor \neg p\) and \(\beta = p\) and the full model is a counterexample.

So far, we have seen the \(\alpha\)s in the valid \(\text{Kh}\alpha\) formulas behave pretty much like the valid formulas in the inquisitive logic, we will show it is no coincidence.

### 3.3 \(\text{InqKhL} = \text{InqB}\)

In this subsection, we show \(\text{InqKhL} = \{\alpha \in \text{PL} \mid \models \text{Kh}\alpha\}\) is exactly the inquisitive logic \(\text{InqB}\). We will actually prove a stronger result showing the corresponding semantics consequences are the same.

**Definition 31** Given any model \(\mathcal{M} = (W, V)\) and a non-empty state \(s \subseteq W\), let \(\mathcal{M}_s\) be the submodel \((s, V|_s)\) where \(V|_s\) is the restriction of \(V\) on \(s\), that is, \(V(w) = V|_s(w)\) for any \(w \in s\).

Here is an easy observation that the worlds outside the given state are irrelevant according to support semantics. This also justifies our notion of \(\models s\) without specifying the model \(\mathcal{M}\) below.

**Proposition 32** Given any two models \(\mathcal{M}\) and \(\mathcal{M}'\), and a state \(s \subseteq W_M\) and \(s \subseteq W_{M'}\), if \(\mathcal{M}_s = \mathcal{M}'_s\), then for any \(\alpha \in \text{PL}\): \(\mathcal{M}, s \models \alpha \iff \mathcal{M}', s \models \alpha\). In particular if \(s\) is non-empty and \(s \subseteq W_M\), then \(\mathcal{M}, s \models \alpha \iff \mathcal{M}_{s}\).

Now we establish the logical equivalence between \(\mathcal{M}\) and \((\mathcal{M}, W_M)\) where \(W_M\) is viewed as the trivial state.

**Lemma 33** Given any \(\alpha \in \text{PL}\) and any pointed model \(\mathcal{M}, w\),

\[\mathcal{M}, w \models \text{Kh}\alpha \iff \mathcal{M} \models \text{Kh}\alpha \iff \mathcal{M}, W_M \models \alpha.\]

**Proof** By Proposition 18 we only need to show that for any model \(\mathcal{M}\), \(\mathcal{M} \models \text{Kh}\alpha\) iff \(W_M \models \alpha\). We prove the lemma by induction on \(\alpha\).

\[\begin{align*}
\mathcal{M} \models \text{Kh}\varphi & \iff \mathcal{M} \models \varphi \quad \text{for each } \varphi \in W_M, \varphi \in V(w) \iff W_M \models \varphi. \\
\mathcal{M} \not\models \text{Kh}\bot & \iff W_M \not\models \bot.
\end{align*}\]

\[\begin{align*}
\mathcal{M} \models \text{Kh}(\alpha \lor \beta) & \iff \mathcal{M} \models \text{Kh}\alpha \lor \text{Kh}\beta \iff \mathcal{M} \models \text{Kh}\alpha \text{ or } \mathcal{M} \models \text{Kh}\beta \iff W_M \models \alpha \text{ or } W_M \models \beta \\
& \iff W_M \models \alpha \lor \beta.
\end{align*}\]

\[\begin{align*}
\mathcal{M} \models \text{Kh}(\alpha \land \beta) & \iff \mathcal{M} \models \text{Kh}\alpha \land \text{Kh}\beta \iff \mathcal{M} \models \text{Kh}\alpha \text{ and } \mathcal{M} \models \text{Kh}\beta \iff W_M \models \alpha \text{ and } W_M \models \beta \\
& \iff W_M \models \alpha \land \beta.
\end{align*}\]

\[\begin{align*}
\mathcal{M} \models \text{Kh}(\alpha \to \beta) & \iff \text{for any } \mathcal{M}' \subseteq \mathcal{M}, \mathcal{M}' \models \text{Kh}\alpha \text{ implies } \mathcal{M}' \models \text{Kh}\beta \text{ (by Proposition 24)} \\
& \iff \text{for any non-empty } s \subseteq W_M, s \models \alpha \text{ implies } s \models \beta \text{ (by IH)} \\
& \iff W_M \models \alpha \to \beta.
\end{align*}\]

Since \(s = W_{(\mathcal{M}, s)}\) for any non-empty state \(s\), as a consequence of Lemma 33 and Proposition 32 we have:

**Proposition 34** For each non-empty state \(s\) in \(\mathcal{M}\), any \(\alpha \in \text{PL}\), \(\mathcal{M}, s \models \alpha \iff \mathcal{M}_s \models \text{Kh}\alpha\).

Now we are ready to establish the relation between \(\text{InqB}\) and \(\text{InqKhL}\).

**Theorem 35** Given any \(\{\alpha\} \cup \Gamma \subseteq \text{PL}\), \(\Gamma \models \alpha \iff \text{Kh}\Gamma \models \text{Kh}\alpha\).

**Proof** First, note that due to Proposition 18 \(\text{Kh}\Gamma \models \text{Kh}\alpha\) iff for any \(\mathcal{M}\), \(\mathcal{M} \models \text{Kh}\Gamma\) implies \(\mathcal{M} \models \text{Kh}\alpha\).

\[
\implies: \text{For any model } \mathcal{M} \text{ s.t. } \mathcal{M} \models \text{Kh}\Gamma, \text{ we have } W_M \models \Gamma \text{ by Lemma 33. Since } \Gamma \models \alpha, \text{ it follows that } W_M \models \alpha. \text{ By Lemma 33 again, we have } \mathcal{M} \models \text{Kh}\alpha. \text{ Therefore } \text{Kh}\Gamma \models \text{Kh}\varphi.
\]
Axioms of perfect recall axiom schemata/rules for $\text{S5}$ e.g., [38]. Per empty state supports all formulas in inquisitive semantics, it follows that $s \models \alpha$. If $s$ is non-empty, by Proposition 34, $M_s \models \K h \Gamma$, thus $M_s \not\models \K h \alpha$. By Proposition 34 again, $s \models \alpha$. As a result, $\Gamma \models \alpha$.

When $\Gamma = \varnothing$, it follows immediately that:

**Corollary 36** $\text{InqB} = \text{InqKhL}$.  

4 Axiomatizing the full logic

We showed in the previous section that $\text{InqKhL} = \text{InqB}$, thus the valid $\K h$-fragment can be axiomatized by the corresponding axioms for inquisitive logic. However, the more interesting question to answer is what the logic with respect to the full language $\text{DELKh}$ is. In this section, we provide a complete axiomatization and also show that the full $\text{DELKh}$-language is equally expressive as the epistemic fragment with $\K$ modality only. The conceptual advantage of our axiomatization is that all the axioms are epistemically intuitive, compared to the axioms of inquisitive logic. The axiomatization also shows the hidden dynamic-epistemic content of inquisitive logic in a clear syntactic manner.

**System SDELKh**

**Axioms**

| Symbols | Axioms                                                                 |
|---------|------------------------------------------------------------------------|
| TAUT    | Propositional tautologies                                             |
| DIST$_{K}$ | $K(\varphi \rightarrow \psi) \rightarrow (K\varphi \rightarrow K\psi)$ |
| T$_{K}$  | $K\varphi \rightarrow \varphi$                                       |
| 4$_{K}$  | $K\varphi \rightarrow KK\varphi$                                     |
| 5$_{K}$  | $\neg K\varphi \rightarrow KK\varphi$                               |
| T$_{\Box}$ | $\Box \varphi \rightarrow \varphi$                                   |
| 4$_{\Box}$ | $\Box \varphi \rightarrow \Box K\varphi$                            |
| PR      | $K \Box \varphi \rightarrow \Box K\varphi$                           |
| Ver     | $\alpha \rightarrow \Diamond \K h \alpha$                           |

**Rules:**

| Rules | Formula  |
|-------|----------|
| MP    | $\varphi, \varphi \rightarrow \psi \vdash \psi$              |
| NEC$_{K}$ | $\vdash \varphi \rightarrow K\varphi$         |
| NEC$_{\Box}$ | $\vdash \varphi, \vdash \Box \varphi$ |

S5 axiom schemata/rules for $\K$ and S4 axiom schemata/rules for $\Box$ are expectable. PR is the axioms of perfect recall often assumed in temporal epistemic logic and dynamic epistemic logic (cf. e.g., [38]). Per says the truth values of propositional formulas do not change given informational updates. Ver says that propositional truth is eventually verifiable. For any finite set of worlds in the current model, $\{\text{EU}_k \mid k \in \mathbb{N}\}$ ensures the existence of an updated submodel that contains exactly the current world and that set of worlds. We will use EU$_k$ to prove the reduction formula BK$\Box$ in Appendix A. K$\K h$ says that know-how is stronger than know-that. KK$K p$, K$\bot$, K$\lor$, K$\land$, K$\rightarrow$ are the reduction axioms decoding the inquisitive formulas. Introspection schemata 4$K$, 4$\K h$, and 5$\K h$ can be proved from the rest of the system. In particular, 4$K h$ requires an inductive proof on the structure of $\alpha$. We include them for the sake of their intuitive meanings.

**Theorem 37 (Soundness)** SDELKh is sound over the class of all epistemic models.

**Proof** The validity of S5 axiom schemata/rules for K and S4 axiom schemata/rules for $\Box$ are immediate. Based on Propositions 18, 20, 21, 28 and 23, we only need to check PR and Ver. For PR, it is easier to verify its dual form $\Diamond K\varphi \rightarrow K \Diamond \varphi$; if there is a submodel where $\varphi$ holds at some world then there is a world and a submodel including it where $\varphi$ holds. Ver is valid since moving
to any submodel does not change the valuation of the current world. $$\text{EU}_K$$ is valid because as long as the current world sees a (finite) set of worlds, we can take the submodel that contains both the current world and the set of worlds as the witness for $$\Diamond$$.

Note that we do not have the rule of uniform substitution for this system in general (recall Example [1]). Moreover, even the rule of monotonicity for $$K_h$$ is not valid, e.g., $$\vdash \neg\neg\alpha \rightarrow \alpha$$ but $$\not\vdash K_h\neg\neg\alpha \rightarrow K_h\alpha$$.

However, since we have TAU\textsc{T} and the modalities of $$\Box$$ and $$K$$ are normal, we can have the admissible rule r\textsc{RE} of replacement of equals by equals if we treat all the $$K_h\alpha$$ as atomic formulas when doing the substitutions:

$$\text{rRE} : \quad \vdash \varphi \leftrightarrow \psi \quad \text{given that the substitution does not happen in the scope of } K_h.$$  

Due to $$\text{NEC}_K\hspace{1pt}$$, $$\text{NEC}_\Box$$ and the axiom $$K_h\rightarrow$$, another useful admissible rule is the syntactic analog of (the non-trivial side of) Proposition [25]

$$\text{RKh\rightarrow} : \quad \vdash K_h\alpha \rightarrow K_h\beta \quad \vdash K_h(\alpha \rightarrow \beta)$$

To prove the completeness we need some extra provable (technical) formulas inspired by the reduction of the arbitrary announcement operator in [1] in the single-agent case.

**Proposition 38** The following schemata are provable in SDELKh, where $$\alpha \in \text{PL}$$ and $$\varphi \in \text{DEL}$$ (i.e., $$K_h$$-free).

$$\begin{align*}
\text{INV} & : \quad \Box \alpha \leftrightarrow \alpha \\
\text{BK} & : \quad \Box(\alpha \lor \varphi) \leftrightarrow \Box \alpha \lor \Box \varphi \\
\text{KINV} & : \quad K\Box \alpha \leftrightarrow K\alpha \\
\text{hKINV} & : \quad K\Box \alpha \leftrightarrow \alpha
\end{align*}$$

**Proof** INV is the combination of Perx and T\textsc{Q}. KINV is proved from Perx and PR. hKINV is a special instance of BK\textsc{V} when $$n = 0$$. We include the (tedious) proofs of the other two formulas in Appendix A.

Recall that $$\text{DEL}$$ is the $$K_h$$-free fragment of DELKh, and EL is the $$\Box$$-free fragment of DEL. By the following lemmata, we show that each DELKh-formula is provably equivalent to an EL-formula.

**Lemma 39** Each DELKh-formula is provably equivalent to a DEL-formula in SDELKh.

**Proof** Note that with the help of r\textsc{RE}, we can repeatedly apply Axioms Kh\textsc{S}, Kh\textsc{V}, Kh\textsc{→} step by step to reduce $$K_h\alpha$$ to simpler $$K_h$$ formulas. It is not hard to show that eventually, all the $$K_h$$-formula can be reduced to some formulas with $$K_h\Box$$ only. By Axioms KhK and KKKh, we have $$\vdash K_h\Box \rightarrow K_h\Box$$, which will eventually eliminate any $$K_h$$ modality completely.

**Lemma 40** Each DEL-formula is provably equivalent to an EL-formula in SDELKh.

**Proof** Here we follow the idea in [1]. We say a formula $$\varphi \in \text{EL}$$ is in normal form if it is a conjunction of disjunctions of the form $$\alpha \lor K\alpha_0 \lor K\alpha_1 \lor \cdots \lor K\alpha_n$$ where $$\alpha, \alpha_0, \ldots, \alpha_n \in \text{PL}$$. Every formula in single-agent S5 is equivalent to a formula in normal form [24]. So we only need to prove that $$\Box(\alpha \lor K\alpha_0 \lor K\alpha_1 \lor \cdots \lor K\alpha_n)$$ is provably equivalent to an EL formula in SDELKh. Then we can eliminate the $$\Box$$ step by step from the innermost ones that do not have any $$\Box$$ in its scope.

By BV, $$\Box(\alpha \lor K\alpha_0 \lor K\alpha_1 \lor \cdots \lor K\alpha_n)$$ is equivalent to $$\alpha \lor \Box(K\alpha_0 \lor K\alpha_1 \lor \cdots \lor K\alpha_n)$$, and by BKV, $$\alpha \lor \Box(K\alpha_0 \lor K\alpha_1 \lor \cdots \lor K\alpha_n)$$ is equivalent to $$\alpha \lor K\alpha_0 \lor K(\alpha_0 \lor \alpha_1) \lor \cdots \lor K(\alpha_0 \lor \alpha_n)$$, which is a formula in EL. Note that BV and BKV are provable in SDELKh as shown by Proposition 38.
Lemmata 39 and 40 together with Theorem 37 also tell us about the expressivity of \( \text{DELKh} \).

**Theorem 41 (Expressivity)** \( \text{DELKh} \) is equally expressive as \( \text{EL} \) over epistemic models.

In particular, we have the following corollary.

**Corollary 42** For each \( \alpha \in \text{PL} \), there is an epistemic formula \( \phi \in \text{EL} \) such that
\[
\mathcal{M}, W_M \models \alpha \iff \mathcal{M}, w \models \text{Kh} \phi \iff \mathcal{M}, w \models \phi.
\]

As shown in the literature, a simple direct translation from inquisitive logic to epistemic logic will be given in Section 6.

**Theorem 43 (Completeness)** \( \text{SDELKh} \) is complete over the class of all epistemic models.

**Proof** We prove the completeness by translating each \( \text{DELKh} \)-formula \( \phi \) into an equivalent \( \text{EL} \)-formula \( \phi' \) and follow the strategy below.

\[
\begin{align*}
\models \phi & \iff \text{expressive equivalence} \iff \models \phi' \iff \text{completeness of S5} \iff \text{S5} \subseteq \text{SDELKh} \iff \vdash \text{SDELKh} \phi' \iff \text{provable equivalence} \iff \vdash \text{SDELKh} \phi.
\end{align*}
\]

Strong completeness can be obtained in the similar process w.r.t. a given assumption set \( \Gamma \) (cf. e.g., [2]). Decidability of \( \text{SDELKh} \) immediately follows from the proofs of the above theorems and the decidability of S5.

**Corollary 44** \( \text{SDELKh} \) is decidable.

To demonstrate the power and the use of our system, we show that the following important axioms can be proved based on our intuitive epistemic axioms. In particular, compared to the semantic validity of \( \text{KhDNp} \) shown in Proposition 39, the syntactic proof of \( \text{KhDNp} \) presents the non-trivial use of the axioms regarding \( \Box \) and \( \text{K} \) in Proposition 38.

**Proposition 45** The following are provable in \( \text{SDELKh} \):
\[
\begin{align*}
\text{KKhN} & \quad \text{K} \neg \alpha \to \text{Kh} \neg \alpha \\
\text{KhdNp} & \quad \text{Kh}(\neg \neg p \to p) \\
\text{KhNDk} & \quad \text{Kh}((\neg \alpha \to \vee_{1 \leq i \leq k} \neg \beta_i) \to \vee_{1 \leq i \leq k} (\neg \alpha \to \neg \beta_i))
\end{align*}
\]

**Proof** For \( \text{KKhN} \):
\[
\begin{align*}
\vdash \text{Kh} \alpha & \iff \alpha & \text{KKh, T}_K, \text{TAUT} \quad (1) \\
\vdash \neg \alpha & \iff \neg \text{Kh} \alpha & \text{TAUT} \quad (2) \\
\vdash \Box \neg \alpha & \iff \Box \neg \text{Kh} \alpha & \text{NEC}_\Box \quad (3) \\
\vdash \neg \alpha & \iff \Box \neg \text{Kh} \alpha & \text{Per}, \text{TAUT} \quad (4) \\
\vdash \text{K} \neg \alpha & \iff \text{K} \neg \text{Kh} \alpha & \text{NEC}_K \quad (5) \\
\vdash \text{K} \neg \alpha & \iff \text{K} (\alpha \to \text{Kh} \bot) & \text{KhL}, \text{rRE} \quad (6) \\
\vdash \text{K} \neg \alpha & \iff \text{K} \neg \alpha & \text{Kh} \to, \text{rRE} \quad (7)
\end{align*}
\]

For \( \text{KhdNp} \):
\[
\begin{align*}
\vdash (\neg \neg p \to p) & \iff \text{TAUT} \quad (1) \\
\vdash \text{Kh}(\neg \neg p \to p) & \iff \text{NEC}_K \quad (2) \\
\vdash \text{K} \neg \neg p & \iff \text{K} p & \text{DIST}_K, \text{MP} \quad (3) \\
\vdash \text{Kh} \neg \neg p & \iff \text{Kh} \neg p & \text{KhK} \quad (4)
\end{align*}
\]

16
In this section, we look at the concepts in inquisitive semantics from our alternative epistemic framework, it does not hold in general when other hand,

\[ \vdash Kp \rightarrow Khp \]  
(5)

\[ \vdash Kh\neg p \rightarrow Khp \]  
(6)

\[ \vdash Kh(\neg p \rightarrow p) \]  
(7)

For KhND,

\[ \vdash K\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i) \rightarrow \bigvee_{1 \leq i \leq k} (K\alpha \lor K(\alpha \lor \neg \beta_i)) \]  
TAUT  
(1)

\[ \vdash K(\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i)) \leftrightarrow (K\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i)) \]  
S5K  
(2)

\[ \vdash K(\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i)) \leftrightarrow (K\alpha \lor K(\alpha \lor \neg \beta_i)) \]  
S5K  
(3)

\[ \vdash K(\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i)) \rightarrow \bigvee_{1 \leq i \leq k} (K\alpha \lor K(\alpha \lor \neg \beta_i)) \]  
(1) (2) (3) rRE  
(4)

\[ \vdash \Box (K\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i)) \leftrightarrow (\alpha \lor \bigvee_{1 \leq i \leq k} K(\alpha \lor \neg \beta_i)) \]  
BK\lor  
(5)

\[ \vdash \Box (K\alpha \lor K(\neg \beta_i)) \leftrightarrow (\alpha \lor K(\alpha \lor \neg \beta_i)) \]  
BK\lor  
(6)

\[ \vdash \Box (K\neg \alpha) \rightarrow \bigvee_{1 \leq i \leq k} K(\neg \beta_i) \rightarrow \bigvee_{1 \leq i \leq k} \Box (K\neg \alpha \rightarrow K(\neg \beta_i)) \]  
(1) (2) (3) rRE  
(7)

\[ \vdash \Box (Kh\neg \alpha) \rightarrow \bigvee_{1 \leq i \leq k} Kh\neg \beta_i \rightarrow \bigvee_{1 \leq i \leq k} \Box (Kh\neg \alpha \rightarrow Kh\neg \beta_i) \]  
KhK, KhV, rRE  
(8)

\[ \vdash \Box (Kh\neg \alpha) \rightarrow Kh \bigvee_{1 \leq i \leq k} \neg \beta_i \rightarrow \bigvee_{1 \leq i \leq k} Kh(\neg \alpha \rightarrow \neg \beta_i) \]  
KhV, Kh\rightarrow, rRE  
(9)

\[ \vdash Kh(\neg \alpha) \rightarrow \bigvee_{1 \leq i \leq k} \neg \beta_i \rightarrow Kh \bigvee_{1 \leq i \leq k} (\neg \alpha \rightarrow \neg \beta_i) \]  
Kh\rightarrow, Kh\lor, rRE  
(10)

\[ \vdash Kh((\neg \alpha \rightarrow \bigvee_{1 \leq i \leq k} \neg \beta_i) \rightarrow \bigvee_{1 \leq i \leq k} (\neg \alpha \rightarrow \neg \beta_i)) \]  
(10) rRE  
(11)

Note that although KhND and KhKP are very similar semantically as in the proof of Proposition 30 deriving KhKP requires more efforts within our proof system due to the absence of negations in front of \( \beta_i \), which bracketed \( K \) and \( Kh \) in the above proof. Nevertheless, KhKP can be proved via a detour using Theorem 54 that gives the equivalent \( \bigvee K\beta_i \) form of each Kh-formula, which then reduces the case to KhND.

To end this section, we discuss the connections of our logic of knowing how with the planning-based knowing how logic studied in [35, 14, 20]. In [20], Kh\( \varphi \) roughly says that there is a plan such that I know that executing it will always guarantee \( \varphi \), where \( \varphi \) can be any formula in the language. Note that this is very different from the intuitive reading of know-how operator in the current framework, where Kh\( \alpha \) says that knowing how \( \alpha \) is true, where \( \alpha \) is a propositional formula. The fundamental difference in the semantics is reflected by the axioms regarding the Kh modality. For example, Kh(\( \varphi \lor \psi \)) \rightarrow (Kh\( \varphi \lor Kh\psi \)) is not valid in [14, 20], e.g., one can always use any plan to make sure \( p \lor \neg p \) but it does not mean one can make sure \( p \lor \neg p \). On the other hand, K\( \varphi \rightarrow Kh\varphi \) is valid in [14, 20] since you can always use the empty plan, whereas in our framework, it does not hold in general when \( \varphi \) is not a statement.

### 5 Epistemic interpretation of inquisitive semantics

In this section, we look at the concepts in inquisitive semantics from our alternative epistemic perspective.

\(^5\)Instead of EU<sub>1</sub>, we may try to add an axiom \( K\Box (K\alpha \land \neg Kh\beta) \land \neg Kh\Box (K\alpha \land \neg Kh\gamma) \rightarrow Kh\Box (K\alpha \land \neg Kh\beta \land \neg Kh\gamma) \), which captures the possibility of merging two submodels, thus having a direct link with KhKP (cf. the proof of Proposition 30).
We first summarize the correspondence between our semantics and inquisitive semantics below based on the corresponding definitions in Section 2.

| Inquisitive semantics                      | Our epistemic semantics                      |
|--------------------------------------------|-----------------------------------------------|
| non-empty states                           | single-agent S5 epistemic model (with an implicit total relation) |
| support \((M, s \models \alpha)\)           | epistemic submodels                            |
| alternatives for \(\alpha\) in \(M\)       | know-how \((M, s \models \text{Kh}\alpha)\)   |
| proposition expressed by \(\alpha\) in \(M\)| maximal submodels of \(M\) satisfying \(\text{Kh}\alpha\) |
| \(\alpha\) is inquisitive in \(M\)         | set of submodels of \(M\) for \(\text{Kh}\alpha\) |
| \(\alpha\) is informative in \(M\)         | there are two maximal submodels satisfying \(\text{Kh}\alpha\) |
|                                              | there is one world not in any maximal submodels of \(M\) for \(\text{Kh}\alpha\) |

First we give an epistemic characterization of informativeness (and questions). The idea is that \(\alpha\) is informative iff you do not know that \(\alpha\) already.

**Proposition 46** Given any \(M\), \(\alpha\) is informative in \(M\) iff \(M \models \neg \text{Kh}\alpha\). Thus \(\alpha\) is a question in \(M\) iff \(M \models \text{Kh}\alpha\).

**Proof** Recall that \(\alpha\) is informative in \(M\) iff there is at least one world in \(M\) that is not included in any alternative for \(\alpha\) in \(M\) (cf. Definition 9). This definition can be rendered intuitively (and formally) as \(M \models \neg \text{K} \neg \neg \text{K} \alpha\) in our framework. Now due to Proposition 28, it is equivalent to \(M \models \text{K} \neg \text{K} \neg \alpha\), namely, \(M \models \neg \text{Kh}\alpha\). Next, we prove an epistemic characterization of inquisitiveness and statements. The idea is that \(\alpha\) is inquisitive in \(s\) iff it is possible to know \(\alpha\) while not knowing how to resolve it with the information provided by \(s\) in a model \(M\).

**Proposition 47** Given any \(M\), \(\alpha\) is inquisitive in \(M\) iff \(M \models \text{K} \neg \text{K} \neg \neg \text{K} \alpha\wedge \neg \text{K} \neg \text{Kh} \alpha\). Thus \(\alpha\) is a statement in \(M\) iff \(M \models \text{K} \text{P} (\text{K} \alpha \rightarrow \text{Kh} \alpha)\).

**Proof** Recall that \(\alpha\) is inquisitive in \(M\) iff there are at least two alternatives for \(\alpha\) (cf. Definition 9). In our terms, it means there is some submodel (e.g., the union of those two alternatives) such that \(\text{K} \alpha\) holds but there is no uniform resolution. Formally, it amounts to \(M \models \text{K} \neg \text{K} \neg \neg \text{K} \alpha \wedge \neg \text{K} \neg \text{Kh} \alpha\). Therefore \(\alpha\) is a statement in \(M\) iff \(\alpha\) is not inquisitive iff \(M \models \text{K} \neg \text{K} \neg \neg \text{K} \alpha\wedge \neg \text{K} \neg \text{Kh} \alpha\) iff \(M \models \text{K} \text{P} (\text{K} \alpha \rightarrow \text{Kh} \alpha)\).

Note that \(\text{K} \text{P} (\text{K} \alpha \rightarrow \text{Kh} \alpha)\) is equivalent to \(\text{Kh} (\neg \neg \alpha \rightarrow \alpha)\) which is consistent with the characterization of statements in 12. \(\text{K} \text{P} (\text{K} \alpha \rightarrow \text{Kh} \alpha)\) says that I know that if you tell me \(\alpha\) is resolvable then I will know how to resolve it.

In particular, when taking a full model \(M\) and the trivial state \(W_M\), then from Propositions 6, 46 and 47, we have the characterization of absolute questions and statements.

**Proposition 48** \(\alpha\) is a question iff \(\text{K} \alpha\) is valid iff \(\alpha\) is a classical tautology. \(\alpha\) is a statement iff \(\text{K} \alpha \rightarrow \text{Kh} \alpha\) is valid iff \(\text{K} \alpha \leftrightarrow \text{Kh} \alpha\) is valid.

Based on the above epistemic characterization of the relative notion of statements, we can prove the following from a purely epistemic perspective extending the result in Proposition 2.19 in 12 about absolute statements.

**Proposition 49** For any \(p \in \mathcal{P}\) and \(\alpha, \beta \in \mathcal{PL}\), any given model \(M\):

1. \(p\) is a statement in \(M\).
2. \(\bot\) is a statement in \(M\).
3. If \(\alpha\) and \(\beta\) are statements in \(M\), then \(\alpha \wedge \beta\) is a statement in \(M\).

\(^6\)If \(V[s] = \mu(P)\) then we have the corresponding absolute notions of inquisitiveness and informativeness as in 12.
4. if \( \beta \) is a statement in \( M \), then \( \alpha \rightarrow \beta \) is a statement in \( M \).

**Proof**  (1) and (2) are trivial. For (3): Suppose \( \alpha \) and \( \beta \) are statements in \( M \), by Proposition \([47]\) we need to show \( M \models K(\alpha \land \beta) \rightarrow Kh(\alpha \land \beta) \), which is equivalent to \( M \models K(\alpha \land K\beta) \rightarrow (Kh\alpha \land Kh\beta) \). By the assumption that \( \alpha \) and \( \beta \) are statements in \( M \), it can be easily proved.

Now for (4): Suppose that \( \beta \) is a statement in \( M \). By Proposition \([47]\) we have \( M \models K(\alpha \rightarrow \beta) \rightarrow Kh\beta \). We need to show that \( M \models K(\alpha \rightarrow \beta) \rightarrow Kh(\alpha \rightarrow \beta) \), namely, for any submodel \( M' \) of \( M \) if \( M' \models K(\alpha \rightarrow \beta) \) then \( M' \models K(\alpha \rightarrow \beta) \rightarrow Kh\beta \). Suppose \( M' \models K(\alpha \rightarrow \beta) \) and take any submodel \( M'' \) of \( M' \) such that \( M'' \models Kh\alpha \), then we only need to show \( M'' \models Kh\beta \). Since \( M'' \models Kh\alpha \rightarrow Kh\beta \), we have \( M'' \models Kh\alpha \rightarrow Kh\beta \). Now due to the fact that \( M'' \) is also a submodel of \( M \), we have \( M'' \models Kh\beta \) by (†), which completes the proof.

As an immediate consequence, any disjunction-free formula is a statement in any \( M \).

**Proposition 50** For any \( \alpha \in PL \), if \( \alpha \) is disjunction-free, then \( \alpha \) is a statement in \( M \) for any \( M \).

Next, we show the epistemic proof of another result in \([12]\) linking the three most important concepts in inquisitive semantics.

**Proposition 51 (Support, inquisitiveness, and informativeness)** \( M, s \) supports a formula \( \alpha \) if \( \alpha \) is neither inquisitive in \( M_s \) nor informative in \( M_s \).

**Proof** It is straightforward in our case due to the validity of \( Kh\alpha \leftrightarrow (K\alpha \land K(\alpha \rightarrow Kh\alpha)) \). The right-to-left implication is due to the validity of the axioms \( T_0 \) and \( T_K \). The left-to-right implication is due to the validity of \( Kh\phi \) and the fact that once we have a uniform resolution for \( \alpha \) then we still have it in any submodel.

As we mentioned earlier, the intended interpretation of inquisitive logic is not about knowledge, and what we are presenting is an alternative interpretation. On the other hand, there are intimate connections between the two interpretations conceptually. We conclude the section by the following discussion on knowledge and information range. Starting from Hintikka \([17]\), knowledge in epistemic logic is defined based on information range: \( \phi \) is known iff in \( \phi \) holds on all the epistemic alternatives of the real world. This notion of knowledge is applied to various fields where the object to which we ascribe the knowledge statement is not an agent at all, such as in distributed system of computer science. Note that in many applications, the so-called “agent” is just a way of talking about the information range. It is also reflected in the technical fact that the classical propositional reasoning can be cast in the epistemic logic such that \( \alpha \models CPL \beta \) iff \( Kh\alpha \models_{SS} K\beta \). Intuitively we can turn a classical propositional entailment from \( \alpha \) to \( \beta \) into an epistemic entailment by if \( \alpha \) is known, then \( \beta \) is also known. As we have seen in Theorem \([35]\) we can generalize it to match the entailment of \( InqB \) with then entailment in our know-how variant of epistemic logic. Moreover, when talking about general knowledge, it is not essential to ask which specific agent the knowledge is ascribed to. Actually, the basic systems of epistemic logic are suitable for this kind of general reasoning, by assuming an idealized reasoner, no matter who exactly knows. From our perspective, when we do not give any special constraints on the information that the agent has, we can actually talk about the general semantic knowledge which is not ascribed to a particular agent. Therefore, to us, there is no drastic conceptual gap between the information model for the inquisitive semantics and epistemic model in our setting. Nevertheless, in concrete applications about real agents, some more detailed constraints on what agents know and what they can learn may be given, which may result in changes of logics (cf. e.g., \([8\) Section 2.8]).

6 Related work

In this section, we first connect the formula-based resolutions studied in the literature of inquisitive logic in \([12\), \([7]\) to our approach, and then compare our work to the related modal logic work in the literature.
6.1 Resolutions in terms of formulas in PL

In our framework, the resolutions defined in Definitions 12 and 14 are not in the object language. It is not hard to check as long as $S(p)$ is a singleton $\{x\}$ and $R(w, p) = S(p)$ iff $p \in V_M(w)$, the semantics will not affect the logic. On the other hand, since the resolutions of atomic propositions are defined simply as themselves, it is possible to express the resolutions using formulas in the object language. In [12], the authors proposed a notion of resolutions expressed by disjunction-free formulas in PL. Here we take the simplified version Definition 8 in [7]:

\[ RL(p) = \{p\} \text{ for } p \in P \]
\[ RL(\bot) = \{\bot\} \]
\[ RL(\alpha \lor \beta) = RL(\alpha) \cup RL(\beta) \]
\[ RL(\alpha \land \beta) = \{\rho \land \sigma \mid \rho \in RL(\alpha) \text{ and } \sigma \in RL(\beta)\} \]
\[ RL(\alpha \rightarrow \beta) = \{\bigwedge_{\rho \in RL(\alpha)}(\rho \rightarrow f(\rho)) \mid f : RL(\alpha) \rightarrow RL(\beta)\} \]

For example, instead of using the explicit functions for the resolutions of $\alpha \rightarrow \beta$, $RL$ uses a conjunction of implications to capture the function. As proved in [12], each element of $R(\alpha)$ is a statement.

The following proposition is stated without a proof in Proposition 9.3 in [12] which can be shown by an inductive proof.

**Proposition 53 ([12])** For any model $M$, state $s$ and formula $\alpha \in PL$,

\[ M, s \vdash \alpha \iff \exists \rho \in RL(\alpha) \text{ such that } M, s \models K\rho \]

where $\rho$ is the set of possible worlds that satisfy $\rho$ classically in $M$.

In our know-how perspective, the above proposition actually establishes the equivalence of the state-based inquisitive semantics to the following alternative epistemic semantics for $K\alpha$.

\[ M, w \models K\alpha \iff \text{there exists a } \rho \in RL(\alpha) \text{ such that } M, w \models K\rho \]

We can establish the following equivalences, without using Proposition 53.

**Theorem 54** For any model $M$ and any non-empty state $s$, and any $\alpha \in PL$, the following are equivalent:

1. $M, s \not\models \alpha$
2. $M, s \models K\alpha$
3. $M, s \models \bigvee_{\rho \in RL(\alpha)} K\rho$
4. $M, s \models K\alpha$

**Proof** (1) iff (2) is due to Proposition 34. (3) iff (4) is based on the definition of $\models$ and the fact that $RL(\alpha)$ is finite. In the following, we show that (2) iff (3) by induction on the structure of $\alpha$, where the definition of $RL$ and classical reasoning play an important role.

- $\alpha = p$ or $\alpha = \bot$: It is obvious since $RL(\alpha) = \{\alpha\}$ and $\models K\alpha \leftrightarrow K\alpha$ in such cases.

\[ \text{Note that what exactly is the resolution of each atomic proposition does not matter, due to our BHK-like semantics for } K\alpha, \text{ which only checks the existence of (uniform) resolutions.} \]

\[ \text{In Definition 9.1 in [12], the resolution formulas (realizations) are based on some normal form.} \]
\( \alpha = \alpha_1 \lor \alpha_2 : M_s \models \Box (\alpha_1 \lor \alpha_2) \iff M_s \models \Box \alpha_1 \lor \Box \alpha_2 \iff M_s \models \bigvee_{\rho \in RL(\alpha_2)} \Box \rho \lor \bigvee_{\rho \in RL(\alpha_2)} \Box \rho \\
\alpha = \alpha_1 \land \alpha_2 : M_s \models \Box (\alpha_1 \land \alpha_2) \iff M_s \models \Box \alpha_1 \land \Box \alpha_2 \iff M_s \models \bigvee_{\rho \in RL(\alpha_1)} \rho \land \bigvee_{\rho \in RL(\alpha_2)} \rho \iff M_s \models \bigvee_{\rho \in RL(\alpha_1)} (\rho \land \rho_2) \iff M_s \models \bigvee_{\rho \in RL(\alpha_2)} \rho \\
\alpha = \alpha_1 \rightarrow \alpha_2 : M_s \models \Box (\alpha_1 \rightarrow \alpha_2) \iff M_s \models \Box (\alpha_1 \rightarrow \alpha_2) \)

Based on the induction hypothesis and the definition of \( RL(\alpha \rightarrow \beta) \) we just need to prove that:

\[
M_s \models \Box \left( \bigvee_{\rho \in RL(\alpha_1)} \Box \rho \rightarrow \bigvee_{\rho \in RL(\alpha_2)} \Box \rho \right) \iff M_s \models \bigvee_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)).
\]

\[
\implies \text{Given } M_s \models \Box \left( \bigvee_{\rho \in RL(\alpha_1)} \Box \rho \rightarrow \bigvee_{\rho \in RL(\alpha_2)} \Box \rho \right), \text{ we need to find a } f : RL(\alpha_1) \rightarrow RL(\alpha_2) \text{ s.t. } M_s \models \bigwedge_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)). \text{ As } RL(\alpha_2) \text{ is not empty, let } \rho_0 \text{ be a fixed element of } RL(\alpha_2) \text{ to be used to define the function } f. \text{ There are two cases to be considered.}
\]

- For any \( \rho \in RL(\alpha_1) \) such that \( M_s \models \Box \neg \rho \), we have \( M_s \models \Box (\rho \rightarrow \rho') \text{ for any } \rho' \in RL(\alpha_2). \)

  We can safely define \( f(\rho) = \rho_0 \).

- For any \( \rho \in RL(\alpha_1) \) such that \( M_s \models \Box \rho \), let \( M_\rho^0 \) be the maximal submodel of \( M_s \) s.t. \( M_\rho^0 \models \Box \rho \). By the semantics of \( K \) and \( \Box \), if \( M_s \models \Box (\bigvee_{\rho \in RL(\alpha_1)} \Box \rho \rightarrow \bigvee_{\rho \in RL(\alpha_2)} \Box \rho) \), then \( M_\rho^0 \models \bigvee_{\rho \in RL(\alpha_2)} \Box \rho \), which means that there is a \( \rho' \in RL(\alpha_2) \) such that \( M_\rho^0 \models \Box \rho' \). As \( M_\rho^0 \) is the maximal submodel of \( M_s \) s.t. \( M_\rho^0 \models \Box \rho, M_s \models \Box (\rho \rightarrow \rho') \). We let \( f(\rho) = \rho' \).

Now we have defined an \( f : RL(\alpha_1) \rightarrow RL(\alpha_2) \) s.t. \( M_s \models \bigwedge_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)) \), which is equivalent to \( M_s \models \Box \left( \bigvee_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)) \right) \).

\[
\iff \text{Suppose } M_s \models \bigvee_{\rho \in RL(\alpha_1)} \bigwedge_{\rho \in RL(\alpha_2)} (\rho \rightarrow f(\rho)) \text{ then there is a } f : RL(\alpha_1) \rightarrow RL(\alpha_2) \text{ s.t. } M_s \models \bigwedge_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)). \text{ This amounts to } M_s \models \bigwedge_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)). \text{ By the usual distribution axiom by of } K, M' \models \bigwedge_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)). \text{ Weakening the consequent, we have } M' \models \bigwedge_{\rho \in RL(\alpha_1)} (\rho \rightarrow f(\rho)) \text{ as well. }
\]

As an immediate consequence, we have the modal translation from InqB to the epistemic logic S5 and the modal logic K. The translation to modal logic K (and other normal modal logics) was mentioned by Ciardelli in [5 Section 6.6], and also in [7 Section 5.4] when discussing the modal approach of [26] to the semantics of questions. Through the correspondence with the know-how semantics (w.r.t. \( \models \)) shown in the above theorem, we can see more intuitively what the translation below is doing.

**Corollary 55 (InqB to S5 and K [6 7])** For \( \alpha \in PL, \alpha \in \text{InqB} \) iff \( \bigvee_{\rho \in RL(\alpha)} \Box \rho \in S5 \) iff \( \bigvee_{\rho \in RL(\alpha)} \Box \rho \in K \)

**Proof** The last iff is due to the fact that for each pointed Kripke model \( M, w \models \neg \bigvee_{\rho \in RL(\alpha)} \Box \rho \) there is an epistemic model \( N, w \models \neg \bigvee_{\rho \in RL(\alpha)} \Box \rho \) where \( N = (\hat{W}_M, \sim, V_M) \) and \( \sim \) is the reflexive, symmetric, transitive closure of the accessibility relation in \( M \). Note that \( \neg \bigvee_{\rho \in RL(\alpha)} \Box \rho \) is equivalent to \( \bigwedge_{\rho \in RL(\alpha)} \Box \neg \rho \).

\[\blacksquare\]
Note that although it is natural to think this translation can be compared to Gödel’s translation of intuitionistic logic to S4, the nature of the two translations are quite different in terms of how to read the modality. In Gödel’s translation, the modality is actually a temporal-epistemic one, namely $K\Box$ in our perspective [37], but the modality here is merely a purely epistemic one.

As another corollary of Theorem 54 the following important property of InqB follows.

Corollary 56 ([12, 5]) Any $\alpha \in PL$ is equivalent to a disjunction of statements/negations in inquisitive logic.

**Proof** From Theorem 54 $\models K\alpha \leftrightarrow \bigvee_{\rho \in RL(\alpha)} K\rho$. Due to Proposition 50 $\rho \in RL(\alpha)$ is a statement. Therefore by Proposition 49 $\models K\alpha \leftrightarrow \bigvee_{\rho \in RL(\alpha)} K\rho$, thus $\models K\alpha \leftrightarrow K\bigvee_{\rho \in RL(\alpha)} \rho$. By the validity of the Rule $\Box K\rightarrow$, we have $\models K(\alpha \leftrightarrow \bigvee_{\rho \in RL(\alpha)} \rho)$. By Corollary 56 we have $\alpha \leftrightarrow \bigvee_{\rho \in RL(\alpha)} \rho \in InqB$.

The above corollaries show that inquisitive logic can be viewed as a fragment of normal epistemic logic technically. However, as argued in [2] regarding the modal approach of [26], those modal formulas do not preserve the surface structure of sentences and questions in the natural language. Actually, as shown by our approach, such a reduction to standard epistemic logic is the result of the assumption in inquisitive logic that each atomic proposition has a unique resolution. In similar settings such as intuitionistic logic and Medvedev logic, this is not possible.

Using our powerful language InqKhl, we can keep the structure of statements and questions as they are in the natural language by $K\alpha$ on the one hand, and reveal its epistemic meaning by the reductions on the other hand. We do not need to take sides between the technical and conceptual convenience.

Yet another consequence of Theorem 54 is about the limitation of inquisitive logic over models.

Corollary 57 Inquisitive logic is less expressive than EL.

**Proof** Note that inquisitive logic can only say things in terms of disjunction over positive $K\alpha$ formulas, thus formulas like $K\rho$ are simply not expressible.

With the classical connectives in hand, we can express various things which were not expressible in the standard inquisitive logic, such as the classical negation of an inquisitive formula $\alpha$ (simply by $\neg K\alpha$) (cf. 28 for the study within the framework of inquisitive logic). The classical connectives and normal know-that modality give us lots of flexibility in capturing mixed reasoning with both inquisitive and classical propositions.

### 6.2 Comparison with inquisitive modal logic

In the literature, inquisitive modal logic is proposed as a conservative extension of normal modal logic by introducing the modality in the language and separating the inquisitive disjunction $\lor$ with the classical disjunction $\lor$ (cf. e.g., [63]). To avoid potential confusion with our $\Box$ modality, we denote the inquisitive modality as $\Box$ in this subsection. With $\Box$ at hand, one can naturally express formulas combining the modality and questions, such as $\Box(p\lor\neg p)$, which says knowing whether $p$ in an epistemic setting. Correspondingly, the information model is extended with a binary relation $R$, not to be confused with the resolution function $R$, to interpret the modality with the following extra semantic clause in Definition 6.1.3 in [6]:

$$\mathcal{M}, s \models \Box \alpha \iff \text{for all } w \in s, \mathcal{M}, R[w] \models \alpha$$

where $R[w] = \{ v \mid w R v \text{ in } \mathcal{M} \}$. When $s$ is a singleton set, we can derive the following semantics for $\Box$ over worlds (Proposition 6.1.4 in [6]):

$$\mathcal{M}, w \models \Box \alpha \iff \mathcal{M}, R[w] \models \alpha$$

By the above support-based semantics, $\Box \alpha$ is always truth-conditional, i.e., $s$ supports $\Box \alpha$ iff it is true at each world $w \in s$ (cf. [6]). When $\alpha$ is also truth-conditional, the above semantics of $\Box \alpha$
over worlds clearly boils down to the Kripke semantics for □: □α is true at w if α is true at each v accessible from w. In [6], a general method of axiomatizing the logic is provided that works with various frame conditions.

Since this is another way of combining modalities and inquisitive connectives, it deserves a comparison with our approach, in particular about the semantics of □ under an epistemic reading and our Kh.

By definition, □ relies on the support relation, while Kh has the ∃K-shape semantics that relies on the resolutions as in Definition [14]. However, they are connected deeply and come down to the same truth condition on pointed models. To see this, first let us consider the special case where R is the total-relation in a model M for inquisitive modal logic. Therefore, for any w ∈ W_M, R[w] is exactly the set of possible worlds W_M. Given M, let s_t be the trivial state W_M, and let w ∈ s_t, the support semantics of □α over s_t collapses into the one for the non-modal α:

\[ M, s_t \models □α \iff M, w \models □α \iff M, w \models □α \]

Note that by Lemma 33, we have:

\[ M, s_t \models □α \iff M, w \models □α \iff M, w \models □α \]

From the above two observations, we can establish that for any α ∈ PL:

\[ M, w \models □α \iff M, w \models □α \]

The above equivalence still holds on models with an arbitrary relation R, not just the total one, given that we generalize our Kh semantics naturally to models with R, as in logics of know-wh (cf. e.g., [36]).

\[ M, w \models □α \iff \text{there exists an } x \text{ s.t. for any } v \in R[w], x \in R(v, α) \]

Under this more general semantics of Kh over models with an arbitrary relation R, we can establish:

\[ M, w \models □α \iff M, R[w] \models □α \iff M, w \models □α \]

The second equivalence is again an application of Lemma 33 under the help of Proposition 52. Essentially, the equivalence is due to the fact that the intended function of Kh is exactly to capture the support relations between a state and an inquisitive formula, and the truth conditional semantics of □ gave R[w] as such a state. Thus the two different routes that Kh and □ take in their apparent differently semantics converge to the same truth condition eventually. This equivalence is also suggested by Propositions 53 and Theorem 54 showing that the support semantics can be viewed as a resolution-based semantics. However, in general, it is not guaranteed that the (re)solution-based semantics, such as the one for Medvedev’s logic, can be transformed into an equivalent state-based semantics over information models, for the structure of resolutions for (atomic) propositions is richer than the mere truth values on each world. In the case of inquisitive logic, the situation is very much simplified by assuming the atomic propositions have one and only possible resolution.

There is also an interesting mismatch between our work and inquisitive modal logic. In our setting, we explicitly separate the different roles of the modalities by using both K and Kh. On the other hand, we use the same symbol ∨ for inquisitive and classical disjunctions. In contrast, in inquisitive modal logic, the modality has a double role to play depending on what is in the scope, while the two disjunctions are differentiated explicitly by distinct symbols.

The difference is firstly conceptual. From our epistemic perspective, the non-classical behavior of logical connectives are due to the implicit epistemic modality Kh. From the more recent perspective of inquisitive logic [6], the separation of the two disjunctions makes it more clear that the inquisitive logic can be viewed as an extension of classical logic with the inquisitive operators. The
difference also leads to various logical properties. For example, since we use the same symbol $\vee$ for these two disjunctions, it can function differently inside and outside the scope of $K$. It follows that the usual unconditional rule of replacement of equals in the scope of a modality is invalid, thus making $K$ a hyperintensional operator. On the other hand, by having $K$ and $Kh$ explicitly, we can differentiate them in the axioms and reveal how negation and atomic propositions can act as bridges to connect the two types of knowledge, as in $Kp \leftrightarrow Khp$ and $K\neg \alpha \leftrightarrow K\neg \alpha$. Note that, thanks to our choice of using the same $\vee$ symbol, the axioms such as $Kh\alpha \rightarrow K\alpha$ can be written in a natural way, without introducing unnecessary translations of formulas. We think each approach has its features and advantages. In particular, the inquisitive modality has the very elegant feature of deriving the semantics of statements in terms of know+embedded questions compositionally (cf. [6, Section 6.2]). The combination of the two approaches can be explored in the future.

Beyond the above connections and differences, $K$ and $\Box$ are very different in the motivation behind them. The point of our $K$ operator is to capture the epistemic content already in the support semantics, while the modality in inquisitive modal logic is to add the modal information into the picture. Moreover, in our framework, further modalities and connectives are used to “open up” the $K$ formulas to reveal their intuitive epistemic readings. In a nutshell, we want to turn the inquisitive formulas into classical ones with also epistemic and dynamic modalities to obtain intuitive epistemic readings of them. For example, our approach also features a dynamic modality $\Box$ to open up $K\Box(\alpha \rightarrow \beta)$ by the equivalent $K\Box(\alpha \rightarrow K\beta)$, i.e., knowing how $\alpha$ implies $\beta$ means knowing that whenever one knows how $\alpha$ is true, one also knows how $\beta$ is true. All these extra modalities and the classical connectives helped us to “decode” the non-classical behaviors of the inquisitive logic, from our epistemic perspective. As our intuitive axioms showed, the information behind the innocent-looking propositional formulas of inquisitive logic is very rich, under the epistemic view of point. Interestingly, as we also showed in the paper, $\Box$ and $K$ can be eliminated eventually.

There is one more distinction to be pointed out. In our setting, the modalities cannot occur in the scope of $K$ operators, but this may not be an essential restriction (at least for the modality $K$), given the discussion on the resolutions for inquisitive modalities (cf. [6, Section 6.3]). We leave the study of the extended language for a future occasion.

As another incarnation of inquisitive modal logic with dynamics, Inquisitive Dynamic Epistemic Logic (InqDEL) is proposed and studied in [13, 32]. Since our approach is also dynamic-epistemic in nature, it also deserves some comparison with InqDEL. Again, our approach is to reveal the dynamic-epistemic structure implicitly in the existing inquisitive logic from the epistemic perspective, whereas InqDEL extends the version of inquisitive semantics with extra epistemic structures and dynamics. In the models of InqDEL, there is an issue function $\Sigma$ assigning each possible world an issue $\Sigma(w)$, i.e., a non-empty, downward closed set of states, satisfying some intuitive epistemic conditions. At each world $w$, the set of epistemically indistinguishable worlds $\sigma(w)$ is then defined as $\bigcup \Sigma(w)$. Moreover, the work of [13] is based on a specific version of inquisitive semantics in [10] where a dichotomous syntax, distinguishing declarative and interrogative sentences is used instead of the unified framework of [12]. On top of this dichotomous language, the know-that modality and an extra modality of entertain are added, where the latter modality can describe the issue currently in concern. In contrast, as we mentioned, the dynamic operator $\Box$ in our setting is merely to capture the inquisitive implication. In the model, we also do not have the structures of issues.

7 Conclusions

This paper is a case study of the general research programme proposed in [37] on “epistemizing intuitionistic logic and its relatives. We showed that, as an alternative interpretation, the
propositional inquisitive logic $\text{InqB}$ can be viewed as a (dynamic) epistemic logic of knowing how over standard S5 epistemic models. In our approach, an inquisitive formula $\alpha$ being supported by a state $s$ is formalized as it is known how to resolve $\alpha$ (or simply knowing how $\alpha$ is true). We start by turning an inquisitive formula $\alpha$ into the equivalent know-how formula $K\alpha$ in our framework. Then by using modalities of know-that $K$ and informational updates $\Box$ based on classical connectives, we can unload the epistemic contents hidden in such know-how formulas $K\alpha$ by reducing the complexity of $\alpha$ step by step. From the point of view of the general programme of [37], $\text{InqB}$ is a particularly interesting case since the corresponding know-how modality can be eventually eliminated based on the fact that the resolution of each atomic proposition is unique, which is the reason that the axiom $\neg\neg p \rightarrow p$ holds for atomic propositions $p$ in inquisitive logic.

In our framework, it amounts to the crucial axiom $Kp \rightarrow K\alpha$, i.e., knowing that $p$ is true implies the apparently stronger knowing how it is true, which can help to reduce the know-how operator eventually. Given such a simplification, technically, we can view inquisitive logic as a fragment of standard epistemic logic.

What we have presented so far is clearly only the beginning of an interesting story regarding the classical “epistemicization” of the intuitionistic logic and its friends. Here we just list a few further directions.

- Given the close connections between inquisitive logic and dependence logic (cf. e.g., [5]), it is definitely interesting to see how we can give epistemic interpretations of dependence logic in various forms, where in the semantics a team can be viewed as an epistemic model. Note that as observed by [9], the crucial notion of disjunction in dependence logic, i.e., the tensor, is not directly definable in inquisitive logic. This also presents a challenge to the epistemicization of dependence logic in our framework since we would like to unload the epistemic content of tensor disjunction in a compositional manner. See [33] for the first attempt.

- As in intuitionistic logic, quantifiers may bring extra complications, so it is interesting to see how we can extend our work to capture the first-order inquisitive logic [3].

- Our approach also opens a natural way to extend inquisitive logic to a multi-agent setting. However, our reduction of the dynamic operator relies on the single-agent setting. It remains to see whether we can still reduce the multi-agent epistemicization of inquisitive logic to the multi-agent S5.

- The interpretation of inquisitive formulas in our setting as knowing how $\alpha$ is true has an obvious connection with truthmaker semantics based on the intuitionistic spirit [15]. The exact connections invite close investigations.

- It is also interesting to see how we can combine the idea of inquisitive modal logics with our work to benefit from both frameworks.

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A Remaining proof for Proposition 38

PROOF In the following, let $S_5K$ be the proof system of $S_5$ including $TK$, $4K$, and $S_5$. For $B\lor$:

1. $\vdash \alpha \leftrightarrow \Box \alpha$  
   $\perp_{\Box \alpha}$ \hfill (1)
2. $\vdash \alpha \lor \Box \varphi \leftrightarrow \Box \alpha \lor \Box \varphi$  
   $\perp_{\Box \alpha \lor \Box \varphi}$ \hfill (2)
3. $\vdash \Box \alpha \lor \Box \varphi \rightarrow \Box (\alpha \lor \varphi)$  
   $S4_{\Box}$ \hfill (3)
4. $\vdash \alpha \lor \Box \varphi \rightarrow \Box (\alpha \lor \varphi)$  
   $\perp_{\Box \alpha \lor \Box \varphi}$ \hfill (4)
5. $\vdash \Box (\alpha \lor \varphi) \rightarrow (\alpha \land \Box (\alpha \lor \varphi)) \lor (\neg \alpha \land \Box (\alpha \lor \varphi))$  
   $\perp$ \hfill (5)
6. $\vdash \neg \alpha \leftrightarrow \Box \neg \alpha$  
   $\perp_{\Box \neg \alpha}$ \hfill (6)
7. $\vdash (\neg \alpha \land \Box (\alpha \lor \varphi)) \leftrightarrow (\neg \alpha \land \Box (\alpha \lor \varphi))$  
   $\perp_{\Box \neg \alpha \land \Box (\alpha \lor \varphi)}$ \hfill (7)
8. $\vdash (\neg \alpha \land \Box (\alpha \lor \varphi)) \leftrightarrow (\neg \alpha \land \Box (\alpha \lor \varphi))$  
   $S4_{\Box}$ \hfill (8)
9. $\vdash \Box (\neg \alpha \land \Box (\alpha \lor \varphi)) \leftrightarrow \Box (\neg \alpha \land \Box (\alpha \lor \varphi))$  
   $S4_{\Box}$ \hfill (9)
10. $\vdash \neg \alpha \lor (\alpha \land \Box (\alpha \lor \varphi)) \to \Box \varphi$  
    $\perp_{\Box \varphi}$ \hfill (10)
11. $\vdash \Box (\alpha \lor \varphi) \to (\alpha \land \Box (\alpha \lor \varphi)) \lor \Box \varphi$  
    $\perp_{\Box \varphi}$ \hfill (11)
12. $\vdash \Box (\alpha \lor \varphi) \to \alpha \lor \Box \varphi$  
    $\perp_{\Box \varphi}$ \hfill (12)
13. $\vdash \Box (\alpha \lor \varphi) \leftrightarrow \alpha \lor \Box \varphi$  
    $\perp_{\Box \varphi}$ \hfill (13)

For $B\lor$: Let $\varphi$ be $(K\alpha \lor K\alpha_1 \lor \cdots \lor K\alpha_n)$ and let $\psi$ be $(\alpha \lor K(\alpha \lor \alpha_1) \lor \cdots \lor K(\alpha \lor \alpha_n))$ below.

1. $\vdash \alpha \rightarrow \Box \alpha$  
   $\perp_{\Box \alpha}$ \hfill (1)
2. $\vdash \Box \alpha \rightarrow \Box K\alpha$  
   $S5_{\Box}$, $S4_{\Box}$ \hfill (2)
3. $\vdash \alpha \rightarrow \Box K\alpha$  
   $\perp_{\Box K\alpha}$ \hfill (3)
4. $\vdash \alpha \rightarrow \Box \varphi$  
   $S5_{\Box}$, $S4_{\Box}$ \hfill (4)
5. $\vdash \alpha \rightarrow (\psi \rightarrow \Box \varphi)$  
   $\perp_{\Box \varphi}$ \hfill (5)
6. $\vdash (\alpha \lor \alpha_1) \rightarrow \Box (\alpha \lor \alpha_1)$  
   $\perp_{\Box \alpha \lor \alpha_1}$ \hfill (6)
7. $\vdash K(\alpha \lor \alpha_1) \rightarrow K\Box (\alpha \lor \alpha_1)$  
   $\perp_{\Box (\alpha \lor \alpha_1)}$ \hfill (7)
8. $\vdash K(\alpha \lor \alpha_1) \rightarrow K\Box (\alpha \lor \alpha_1)$  
   $\perp_{\Box (\alpha \lor \alpha_1)}$ \hfill (8)
9. $\vdash K(\alpha \lor \alpha_1) \rightarrow (K\alpha \lor K\alpha_1)$  
   $\perp_{\Box (K\alpha \lor K\alpha_1)}$ \hfill (9)
10. $\vdash K(\alpha \lor \alpha_1) \rightarrow (K\alpha \lor K\alpha_1)$  
    $\perp_{\Box (K\alpha \lor K\alpha_1)}$ \hfill (10)
11. $\vdash K(\alpha \lor \alpha_1) \rightarrow \Box (K\alpha \lor K\alpha_1)$  
    $\perp_{\Box (K\alpha \lor K\alpha_1)}$ \hfill (11)
12. $\vdash K(\alpha \lor \alpha_1) \rightarrow \Box (K\alpha \lor K\alpha_1)$  
    $\perp_{\Box (K\alpha \lor K\alpha_1)}$ \hfill (12)
13. $\vdash K(\alpha \lor \alpha_1) \rightarrow \Box (K\alpha \lor K\alpha_1)$  
    $\perp_{\Box (K\alpha \lor K\alpha_1)}$ \hfill (13)
14. $\vdash K(\alpha \lor \alpha_i) \rightarrow \Box (K\alpha \lor K\alpha_1)$  
    $\perp_{\Box (K\alpha \lor K\alpha_1)}$ \hfill (14)
15. $\vdash \psi \rightarrow \Box \varphi$  
    $\perp_{\Box \varphi}$ \hfill (15)
16. $\vdash \neg \alpha \land \bigwedge_{1 \leq i \leq k} \Box (\neg \alpha \land \neg \alpha_i) \rightarrow \Box (\neg \alpha \land \bigwedge_{1 \leq i \leq k} \Box (\neg \alpha \land \neg \alpha_i))$  
    $\perp_{\Box (\neg \alpha \land \bigwedge_{1 \leq i \leq k} \Box (\neg \alpha \land \neg \alpha_i)}$ \hfill (16)
17. $\vdash \neg \Box (\alpha \land \bigwedge_{1 \leq i \leq k} \Box (\neg \alpha \land \neg \alpha_i)) \rightarrow \Box (\neg \alpha \land \bigwedge_{1 \leq i \leq k} \Box (\neg \alpha \land \neg \alpha_i))$  
    $\perp_{\Box (\neg \alpha \land \bigwedge_{1 \leq i \leq k} \Box (\neg \alpha \land \neg \alpha_i))}$ \hfill (17)
18. $\vdash \Box \psi$  
    $\perp_{\psi}$ \hfill (18)
19. $\vdash \Box \varphi \leftrightarrow \psi$  
    $\perp_{\psi}$ \hfill (19)

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