Completeness of Epistemic Coalition Logic with Group Knowledge

Thomas Ågotnes and Natasha Alechina
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Abstract
Coalition logic is one of the most popular logics for multi-agent systems. While epistemic extensions of coalition logic have received much attention, existence of their complete axiomatisations has so far been an open problem. In this paper we settle several of those problems. We prove completeness for epistemic coalition logic with common knowledge, with distributed knowledge, and with both common and distributed knowledge, respectively.

1 Introduction
Logics of coalitional ability such as Coalition Logic ($\mathcal{CL}$) [11], Alternating-time Temporal Logic ($\mathcal{ATL}$) [1], and STIT logics [2], are arguably some of the most studied logics in multi-agent systems in recent years. Many different variants of these logics have been proposed and studied, but so far meta-logical results have focused more on computational expressiveness and expressive power and less on completeness, with Goranko’s and van Drimmelen’s completeness proof for $\mathcal{ATL}$ [6], Pauly’s completeness proof for $\mathcal{CL}$ [11] and Broersen and colleagues’ completeness proofs for different variants of STIT logic [4, 3, 9] being notable exceptions.

The main construction in coalitional ability logics is of the form $[G]\phi$, where $G$ is a set of agents and $\phi$ a formula, intuitively meaning that $G$ is effective for $\phi$, or that $G$ can make $\phi$ come true no matter what the other agents do. One of the most studied extension of basic coalitional ability logics is adding knowledge operators of the type found in epistemic logic [5, 10]: both individual knowledge operators $K_i$ where $i$ is an agent, and different types of group knowledge operators $E_G$, $C_G$ and $D_G$ where $G$ is a group of agents, standing for everybody-knows, common knowledge and distributed knowledge, respectively. Combining coalitional ability operators and epistemic operators in general and group knowledge operators in particular lets us express many potentially interesting properties of multi-agent systems, such as [12]:

- $K_i\phi \rightarrow [{\{i}\}]K_j\phi$: $i$ can communicate her knowledge of $\phi$ to $j$
• $C_G \phi \to [G] \psi$: common knowledge in $G$ of $\phi$ is sufficient for $G$ to ensure that $\psi$

• $[G] \psi \to D_G \phi$: distributed knowledge in $G$ of $\phi$ is necessary for $G$ to ensure that $\psi$

• $D_G \phi \to [G] E_G \phi$: $G$ can cooperate to make distributed knowledge explicit

In this paper we study a complete axiomatisation of variants of epistemic coalition logic ($ECL$), extensions of coalition logic with individual knowledge and different combinations of common knowledge and distributed knowledge. Coalition logic, the next-time fragment of $ATL$, is one of the most studied coalitional ability logics, and this paper settles a key open problem: completeness of its epistemic variants.

While epistemic coalitional ability logics have been studied to a great extent, we are not aware of any published completeness results for such logics with all epistemic operators. [12] gives some axioms of $ATEL$, $ATL$ extended with epistemic operators, but does not attempt to prove completeness. Broersen and colleagues [3, 9] prove completeness of variants of STiT logic that include individual knowledge operators, but not group knowledge operators, and [9] concludes that adding group operators is an important challenge.

The rest of the paper is organised as follows. In the next section we first give a brief review of coalition logic, and how it is extended with epistemic operators. We then, in each of the three following sections, consider basic epistemic coalition logic with individual knowledge operators extended with common knowledge, with distributed knowledge, and with both common and distributed knowledge, respectively. For each of these cases we show a completeness result. For the common knowledge case we also show a filtration result. We conclude in Section 6.

2 Background

We define several extensions of propositional logic, and the usual derived connectives, such as $\phi \to \psi$ for $\neg \phi \land \psi$, will be used.

2.1 Coalition Logic

Assume a set $\Theta$ of atomic propositions, and a finite set $N$ of agents. A coalition is a set $G \subseteq N$ of agents. We sometimes abuse notation and write a singleton coalition $\{i\}$ as $i$.

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1In an abstract of a talk given at the LOFT workshop in 2004 [7], the authors propose a full axiomatisation of $ATEL$ with individual knowledge and common knowledge operators with similar axioms. However, neither a completeness proof nor the result itself was published, and a proof indeed does not exist as explained to us in personal communication (Valentin Goranko).
The language of coalition logic ($\mathcal{CL}$) is defined by the following grammar:

$$\phi ::= p \mid \neg \phi \mid \phi \land \phi \mid [G] \phi$$

where $p \in \Theta$ and $G \subseteq N$.

A coalition model is a tuple

$$M = \langle S, E, V \rangle$$

where

- $S$ is a non-empty set of states;
- $V$ is a valuation function, assigning a set $V(s) \subseteq \Theta$ to each state $s \in S$;
- $E$ assigns a truly playable effectivity function $E(s)$ to each state $s \in S$.

An effectivity function \[11\] over $N$ and a set of states $S$ is a function $E$ that maps any coalition $G \subseteq N$ to a set of sets of states $E(G) \subseteq 2^S$. An effectivity function is truly playable \[11, 8\] iff it satisfies the following conditions:

- **E1** \(\forall s \in S \forall G \subseteq N \emptyset \notin E(G)(s)\) (Liveness)
- **E2** \(\forall s \in S \forall G \subseteq N S \in E(G)(s)\) (Safety)
- **E3** \(\forall s \in S \forall X \subseteq S \exists X \notin E(\emptyset)(s) \Rightarrow X \in E(N)(s)\) (N-maximality)
- **E4** \(\forall s \in S \forall G \subseteq N \forall X \subseteq Y \subseteq S X \in E(G)(s) \Rightarrow Y \in E(G)(s)\) (outcome monotonicity)
- **E5** \(\forall s \in S \forall G_1, G_2 \subseteq N \forall X, Y \subseteq S X \in E(G_1)(s) \text{ and } Y \in E(G_2)(s) \Rightarrow X \cap Y \in E(G_1 \cup G_2)(s)\), where $G_1 \cap G_2 = \emptyset$ (superadditivity)
- **E6** \(E^{nc}(\emptyset) \neq \emptyset\), where $E^{nc}(\emptyset)$ is the non-monotonic core of the empty coalition, namely

$$\{X \in E(\emptyset) : \neg \exists Y (Y \in E(\emptyset) \text{ and } Y \subset X)\}$$

An effectivity function that only satisfies E1-E5 is called playable. On finite domains an effectivity function is playable iff it is truly playable \[8\], because on finite domains E6 follows from E1-E5.

An $\mathcal{CL}$ formula is interpreted in a state in a coalition model as follows:

- $M, s \models p$ iff $p \in V(s)$
- $M, s \models \neg \phi$ iff $M, s \nvdash \phi$
- $M, s \models (\phi_1 \land \phi_2)$ iff $(M, s \models \phi_1$ and $M, s \models \phi_2)$
- $M, s \models [G] \phi$ iff $\phi^M \in E(s)(G)$

where $\phi^M = \{t \in S : M, t \models \phi\}$.

Figure \[11\] shows an axiomatisation $\mathcal{CL}$ of coalition logic which is sound and complete wrt. all coalition models \[11\]. The following monotonicity rule is derivable, and will be useful later: $\vdash_{\mathcal{CL}} \phi \rightarrow \psi \Rightarrow \vdash_{\mathcal{CL}} [G] \phi \rightarrow [G] \psi$. 

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2.2 Adding Knowledge Operators

Epistemic extensions of coalition logic were first proposed in \[12\]. They are obtained by extending the language with epistemic operators, and the models with epistemic accessibility relations.

An epistemic accessibility relation for agent $i$ over a set of states $S$ is a binary relation $\sim_i \subseteq S \times S$. We will assume that epistemic accessibility relations are equivalence relations. An epistemic coalition model, henceforth often called simply a model, is a tuple

$$M = \langle S, E, \sim_1, \ldots, \sim_n, V \rangle$$

where $\langle S, E, V \rangle$ is a coalition model and $\sim_i$ is an epistemic accessibility relation over $S$ for each agent $i$.

Epistemic operators come in two types: individual knowledge operators $K_i$, where $i$ is an agent, and group knowledge operators $C_G$ and $D_G$ where $G$ is a coalition for expressing common knowledge and distributed knowledge, respectively. Formally, the language of $\mathcal{CLCD}$ (coalition logic with common and distributed knowledge), is defined by extending coalition logic with all of these operators:

$$\phi ::= p \mid \neg \phi \mid \phi \land \phi \mid [H] \phi \mid K_i \phi \mid C_G \phi \mid D_G \phi$$

where $p \in \Theta$, $i \in N$, $H \subseteq N$ and $\emptyset \neq G \subseteq N$. When $G$ is a coalition, we write $E_G \phi$ as a shorthand for $\bigwedge_{i \in G} K_i \phi$ (everyone in $G$ knows $\phi$).

The languages of the logics $\mathcal{CLX}$, $\mathcal{CLC}$ and $\mathcal{CLD}$ are the restrictions of this language with no $C_G$ and no $D_G$ operators, no $D_G$ operators, and no $C_G$ operators, respectively.

The interpretation of these languages in an (epistemic coalition) model $M$ is defined by adding the following clauses to the definition for $\mathcal{CL}$:

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2In that paper for $\mathcal{ATL}$, $\mathcal{CL}$ is a fragment of $\mathcal{ATL}$. 

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Figure 1: $\mathcal{CL}$: axiomatisation of $\mathcal{CL}$. 

Prop Classical propositional logic

G1 $\neg [G] \bot$
G2 $[G] \top$
G3 $\neg [\emptyset] \rightarrow \phi \rightarrow [N] \phi$
G4 $[G] (\phi \land \psi) \rightarrow [G] \psi$
G5 $[G_1] \phi \land [G_2] \psi \rightarrow [G_1 \cup G_2] (\phi \land \psi)$, if $G_1 \cap G_2 = \emptyset$

MP $\vdash_{\mathcal{CL}} \phi, \phi \rightarrow \psi \Rightarrow \vdash_{\mathcal{CL}} \psi$

RG $\vdash_{\mathcal{CL}} \phi \leftrightarrow \psi \Rightarrow \vdash_{\mathcal{CL}} [G] \phi \leftrightarrow [G] \psi$
\( M, s \models K_i \phi \text{ iff } \forall t \in S, (s, t) \in \sim_i \Rightarrow M, t \models \phi \)
\( M, s \models C G \phi \text{ iff } \forall t \in S, (s, t) \in (\bigcup_{i \in G} \sim_i)^* \Rightarrow M, t \models \phi \)
\( M, s \models D G \phi \text{ iff } \forall t \in S, (s, t) \in \bigcap_{i \in G} \sim_i \Rightarrow M, t \models \phi \)

where \( R^* \) denotes the transitive closure of the relation \( R \). We use \( \models \phi \) to denote the fact that \( \phi \) is valid, i.e., that \( M, s \models \phi \) for all \( M \) and states \( s \) in \( M \).

### 2.2.1 Some Auxiliary Definitions

The following are some auxiliary concepts that will be useful in the following.

A pseudomodel is a tuple \( M = (S, \sim_{i: i \in N}, \{R_G: \emptyset \neq G \subseteq N\}, E, V) \) where \( (S, \sim_{i: i \in N}, E, V) \) is a model and:

- \( R_G \subseteq S \times S \) is an equivalence relation for each \( G \)
- For any \( i \in N \), \( R_i = \sim_i \)
- For any \( G, H, G \subseteq H \) implies that \( R_H \subseteq R_G \)

The interpretation of a \( CLCD \) formula in a state of a pseudomodel is defined as for a model, except for the case for \( D_G \) which is interpreted by the \( R_G \) relation:

\( M, s \models D_G \phi \text{ iff } \forall t \in S, (s, t) \in R_G \Rightarrow M, t \models \phi \)

An epistemic model is a model without the \( E \) function, i.e., a tuple \( \langle S, \sim_1, \ldots, \sim_n, V \rangle \). An epistemic pseudomodel is a pseudomodel without the \( E \) function, i.e., a tuple \( \langle S, \{\sim_i: i \in N\}, \{R_G: \emptyset \neq G \subseteq N\}, V \rangle \).

Finally, a playable (pseudo)model is a (pseudo)model where only conditions E1-E5 on \( E \) hold.

# 3 Coalition Logic with Common Knowledge

In this section we consider the logic \( CLC \), extending coalition logic with individual knowledge operators and common knowledge. We first prove a completeness result, and then show that \( CLC \) admits filtrations.

## 3.1 Completeness

The axiomatisation \( CLC \) is shown in Figure 2. It extends \( CL \) with standard axioms and rules for individual and common knowledge (see, e.g., [5]).

It is easy to show that \( CLC \) is sound wrt. all models.

**Lemma 1 (Soundness)** For any \( CLC \)-formula \( \phi \), \( \vdash_{CLC} \phi \Rightarrow \models \phi \).

In the remainder of this section we show that \( CLC \) also is complete.

**Theorem 1** Any \( CLC \)-consistent formula is satisfied in some model.
Prop Classical propositional logic

G1 $\neg[G] \bot$

G2 $[G] \top$

G3 $\neg[\emptyset] \phi \rightarrow [N] \phi$

G4 $[G](\phi \land \psi) \rightarrow [G] \psi$

G5 $[G_1] \phi \land [G_2] \psi \rightarrow [G_1 \cup G_2](\phi \land \psi)$, if $G_1 \cap G_2 = \emptyset$

MP $\vdash_{CLC} \phi, \phi \rightarrow \psi \Rightarrow \vdash_{CLC} \psi$

RG $\vdash_{CLC} \phi \leftrightarrow \psi \Rightarrow \vdash_{CLC} [G] \phi \leftrightarrow [G] \psi$

K $K_i(\phi \rightarrow \psi) \rightarrow (K_i \phi \rightarrow K_i \psi)$

T $K_i \phi \rightarrow \phi$

4 $K_i \phi \rightarrow K_i K_i \phi$

5 $\neg K_i \phi \rightarrow K_i \neg K_i \phi$

C1 $E_i \phi \leftrightarrow \bigwedge_{i \in G} \neg K_i \phi$

C2 $C G \phi \rightarrow E_i (\phi \land C G \phi)$

RN $\vdash_{CLC} \phi \Rightarrow \vdash_{CLC} K_i \phi$

RC $\vdash_{CLC} \phi \rightarrow E_i (\phi \land \psi) \Rightarrow \vdash_{CLC} \phi \rightarrow C G \psi$

Figure 2: CLC: axiomatisation of CLC.

Proof We define a canonical playable model $M^c = (S^c, \{\sim^c_i : i \in N\}, E^c, V^c)$ as follows:

$S^c$ is the set of all maximally CLC consistent sets of formulas

$s \sim^c_i t$ iff $\{\psi : K_i \psi \in s\} = \{\psi : K_i \psi \in t\}$

$X \in E^c(G)(s)$ iff

$\begin{cases} 
\exists \phi \{s \in S^c : \phi \in s\} \subseteq X : [G] \phi \in s & G \neq N \\
\forall \phi \{s \in S^c : \phi \in s\} \subseteq S^c \setminus X : [\emptyset] \phi \notin s & G = N
\end{cases}$

$V^c : s \in V^c(p)$ iff $p \in s$

The conditions on $\sim^c_i$ (that it is an equivalence relation) and on $E^c$ (that it satisfies E1-E5) hold in $M^c$. The proof for $\sim^c_i$ is obvious and the proof for $E^c$ is standard. The intuition of cause is that a formula belongs to a state $s$ in a model iff it is true there (truth lemma). However, the canonical model is in general not guaranteed to satisfy every consistent formula in the CLC language; the case of $C G$ in the truth lemma does not necessarily hold. Therefore we
are going to transform \( M^c \) by filtration into a finite model for a given CLC consistent formula \( \phi \). Note that since \( \phi \) is consistent, it will belong to at least one \( s \) in \( M^c \).

Let \( \text{cl}(\phi) \) be the set of subformulas of \( \phi \) closed under single negations and the condition that \( C_G \psi \in \text{cl}(\phi) \Rightarrow K_i C_G \psi \in \text{cl}(\phi) \) for all \( i \in G \). We are going to filtrate \( M^c \) through \( \text{cl}(\phi) \). The resulting model \( M^f = (S^f, \{ \sim^f_i : i \in N \}, E^f, V^f) \) is constructed as follows:

\( S^f \) is \( \{ [s]_{\text{cl}(\phi)} : s \in S^c \} \) where \( [s]_{\text{cl}(\phi)} = s \cap \text{cl}(\phi) \). We will omit the subscript \( \text{cl}(\phi) \) in what follows for readability.

\[ [s] \sim^f_i [t] \iff \{ \psi : K_i \psi \in [s] \} = \{ \psi : K_i \psi \in [t] \} \]

\[ V^f(p) = [V^c(p)]_{\text{cl}(\phi)} \text{ (where } [X]_{\text{cl}(\phi)} = \{ [s] : s \in X \}) \]. Again we will omit the subscript for readability.

\[ X \in E^f(G)([s]) \text{ if } \{ s' : \phi_X \in s' \} \in E^c(G)(s) \text{ where } \phi_X = \lor_{i \in X} \phi_{[t]} \text{ and } \phi_{[t]} \text{ is a conjunction of all formulas in } [t]. \]

We now prove by induction on the size of \( \theta \) that for every \( \theta \in \text{cl}(\phi) \), \( M^f, [s] \models \theta \) iff \( \psi \in [s] \).

case \( \theta = p \) trivial

case \textbf{booleans} trivial

case \( \theta = K_i \psi \) assume \( M^f, [s] \nvDash K_i \psi \). The latter means there is a \( [s'] \) such that \( [s] \sim^f_i [s'] \) and \( M^f, [s'] \nvDash \phi \). By the inductive hypothesis \( \phi \notin [s'] \).

Since \( [s'] \) is deductively closed wrt \( \text{cl}(\phi) \) and \( K_i \psi \in \text{cl}(\phi) \), also \( K_i \psi \notin [s'] \).

\( [s] \sim^f_i [s'] \) means that \( [s] \) and \( [s'] \) contain the same \( K_i \) formulas from \( \text{cl}(\phi) \), hence \( K_i \psi \notin [s] \).

Assume \( M^f, [s] \models K_i \psi \). Then for all \( [s'] \) such that \( [s] \sim^f_i [s'] \), \( M^f, [s'] \models \psi \). This means by the IH that \( \psi \in [s'] \) for all \( [s'] \sim^f_i [s] \). Assume by contradiction that \( K_i \psi \notin [s'] \). Then \( \phi_{[s]} \), where \( \phi_{[s]} \) is the conjunction of all formulas in \( [s] \), is consistent with \( \neg K_i \psi \). If we write \( (K_i) \) for the dual of the \( K_i \) modality, this is equivalent to: \( \phi_{[s]} \land (K_i) \neg \psi \) is consistent. By forcing choices,

\[ \phi_{[s]} \land (K_i) \bigvee_{\neg \psi \in [t]} \phi_{[t]} \]

is consistent. By the distributivity of \( (K_i) \) over \( \lor \),

\[ \bigvee_{\neg \psi \in [t]} (\phi_{[s]} \land (K_i) \phi_{[t]}) \]

is consistent. So for some \( [t] \) with \( \neg \psi \in [t] \), \( \phi_{[s]} \land (K_i) \phi_{[t]} \) is consistent. We claim that \( [s] \sim^f_i [t] \). If this is the case, we have a contradiction, since we assumed that \( \psi \in [s'] \) for all \( [s'] \sim^f_i [s] \).
Proof of the claim: if \( \phi[s] \land (K_i)\phi[t] \) is consistent, then \([s] \sim^f_t \) [t]. Suppose not \([s] \sim^f_t \) [t], that is there is a formula \( \chi \) such that \( K_i \chi \in [s] \) and \( \neg K_i \chi \in [t] \) or vice versa. Then we have \( K_i \chi \land \phi[s] \land (K_i)(\neg K_i \chi \land \phi[t]) \) is consistent, but since \( K_i \) is an S5 modality, this is impossible. Same for the case when \( \neg K_i \chi \in [s] \) and \( K_i \chi \in [t] \).

**Case \( \theta = [G] \psi \)**

\( M^f, [s] \models [G] \psi \)iff \( \psi^{M^f} \in E^f(G)([s]) \) iff \{ \( s' : (\forall \phi \in \psi^{M^f} \phi[t]) \in s' \} \in E^c(G)(s) \) iff (by the IH) \{ \( s' : (\forall \psi \in [t] \phi[t]) \in s' \} \in E^c(G)(s) \) iff \( \{ \psi : \psi \in s' \} \in E^c(G)(s) \) iff \( [G] \psi \in s \) iff (since \([G] \psi \in cl(\phi)\) \( [G] \psi \in [s] \). The proof is similar to \([13]\). First we show that in \( M^f \), if \( \forall \psi \in [t] \phi[t] \) then every state on every \( \psi \) path is of 0 length, then clearly by deductive closure and by \( \psi \in cl(\phi) \) we have \( \psi \in [s] \). We also have \( C_G \psi \in [s] \) by the assumption. IH: if \( C_G \psi \in [s] \), then every state on every \( \psi \) path of length \( n \) from \([s] \) contains \( \psi \) and \( C_G \psi \). Inductive step: let us prove this for paths of length \( n + 1 \). Suppose we have a path \([s] \sim^f_{i_1} [s_1] \ldots \sim^f_{i_n} [s_n] \sim^f_{i_{n+1}} [s_{n+1}] \). By the
IH, \(\psi, C_G \psi \in [s_n]\). Since \(s_n\) is deductively closed and \(K_{i_{n+1}} C_G \psi \in cl(\phi)\), we have \(K_{i_{n+1}} C_G \psi \in [s_n]\). Since \([s_n] \sim^{f}_{i_{n+1}} [s_{n+1}]\) and the definition of \(\sim^{f}_{i_{n+1}}\), \(C_G \psi \in [s_{n+1}]\) and hence by reflexivity \(\psi \in [s_{n+1}]\).

For the other direction, suppose that every state on every \(\cup_{t \in G} \sim^{f}\) path from \([s]\) contains \(\psi\). Prove that \(C_G \psi \in [s]\). Let \(S_{G,\psi}\) be the set of all \([t]\) such that every state on every \(\cup_{t \in G} \sim^{f}\) path from \([t]\) contains \(\psi\). Note that each \([t]\) is/ corresponds to a finite set of formulas so we can write its conjunction \(\phi_{[t]}\). Consider a formula

\[
\chi = \bigvee_{[t] \in S_{G,\psi}} \phi_{[t]}
\]

Similarly to [13] it can be proved that \(\vdash_{CLC} \phi_{[s]} \rightarrow \chi\), \(\vdash_{CLC} \chi \rightarrow \psi\) and \(\vdash_{CLC} \chi \rightarrow E_G \chi\). And from that follows that \(\vdash_{CLC} \phi_{[s]} \rightarrow C_G \psi\) hence \(C_G \psi \in [s]\).

Now we prove that \(M^f, [s] \models \psi\) iff \(C_G \psi \in [s]\). \(C_G \psi \in [s]\) iff every state on every \(\cup_{t \in G} \sim^{f}\) path from \([s]\) contains \(\psi\) iff for every \([t]\) reachable from \([s]\) by a \(\cup_{t \in G} \sim^{f}\) path, \(M^f, [t] \models \psi\) iff \(M^f, [s] \models C_G \psi\).

\(\square\)

It is obvious that in \(M^f, \sim^f\) are equivalence relations. So what remains to be proved is that \(E^f\) satisfies E1-E6. Since \(S^f\) is finite, it suffices to show E1-E5, which for finite sets of states entail E6.

**Proposition 1** \(M^f\) satisfies E1-E5.

**Proof E1** Note that \(\phi_\bot\) is an empty disjunction, namely \(\bot\).

\(\emptyset \in E^f(G)([s])\) iff (by definition of \(E^f\)) \(\{s' : \bot \in s'\} \in E^c(G)(s)\) iff \(\emptyset \in E^c(G)(s)\). Since \(E^c\) satisfies E1, \(\emptyset \notin E^f(G)([s])\).

**E2** \(E^f(G)([s])\) iff \(\{s' : \forall_{t \in S} t \in s'\} \in E^c(G)(s)\) iff \(s' \in E^c(G)(s)\). Since \(E^c\) satisfies E2, \(S^f \in E^f(G)([s])\).

**E3** Let \(X \notin E^f(\emptyset)([s])\). Then \(\{s' : \phi_X \in s'\} \notin E^c(\emptyset)(s)\). Note that \(\{s' : \phi_X \in s'\} \) is the complement of \(\{s' : \phi_X \in s'\}\), since \(\phi_X = \neg \phi_X\). Since \(E^c\) satisfies E3, this means that \(\{s' : \phi_X \in s'\} \in E^c(N)(s)\). Hence \(X \in E^f(N)([s])\).

**E4** Let \(X \subseteq Y \subseteq S^f\) and \(X \in E^f(G)([s])\). Clearly \(\vdash_{CLC} \phi_X \rightarrow \phi_Y\). Hence \(\{s' : \phi_X \in s'\} \subseteq \{s' : \phi_Y \in s'\}\). Since \(X \in E^f(G)([s])\), we have \(\{s' : \phi_X \in s'\} \in E^c(G)(s)\). Since \(E^c\) satisfies E4, \(\{s' : \phi_Y \in s'\} \in E^c(G)(s)\) so \(Y \in E^f(G)([s])\).

**E5** Let \(X \in E^f(G_1)([s])\) and \(Y \in E^f(G_2)([s])\) and \(G_1 \cap G_2 = \emptyset\). So \(\{s' : \phi_X \in s'\} \in E^c(G_1)(s)\) and \(\{s' : \phi_Y \in s'\} \in E^c(G_2)(s)\) and since \(E^c\) satisfies E5, \(\{s' : \phi_X \in s'\} \cap \{s' : \phi_Y \in s'\} \in E^c(G_2)(s)\). Note that

\[
\{s' : \phi_X \in s'\} \cap \{s' : \phi_Y \in s'\} = \{s' : (\vee_{[t] \in X} \phi_{[t]}) \in s'\} \cap \{s' : (\vee_{[t] \in Y} \phi_{[t]}) \in s'\}
\]
which is in turn the same as
\[
\{s' : (\forall t \in X \cap Y \phi[t] \in s') \}
\]
since \(\{s' : (\forall t \in X \cap Y \phi[t] \in s') \in E^c(G_2)(s), X \cap Y \in E^f(G_1)([s]).\)

\begin{corollary}
For any CLC-formula \(\phi\), \(\vdash_{CLC} \phi \iff \models \phi\).
\end{corollary}

4 Completeness of Coalition Logic with Distributed Knowledge

In this section we consider the logic \(CLD\), extending coalition logic with individual knowledge operators and distributed knowledge.

The axiomatisation \(CLD\) is shown in Figure 3. It extends \(CL\) with standard axioms and rules for individual and distributed knowledge (see, e.g., [5]).

As usual, soundness can easily be shown.

\begin{lemma}[Soundness]
For any \(CLD\)-formula \(\phi\), \(\vdash_{CLD} \phi \Rightarrow \models \phi\).
\end{lemma}

In the remainder of this section we show that \(CLD\) also is complete.

For a set of formulae \(s\), let \(K_a s = \{K_a \phi : K_a \phi \in s\}\) and \(D_s G = \{D_G \phi : D_G \phi \in s\}\).

\begin{definition}[Canonical Playable Pseudomodel]
The canonical playable pseudomodel \(M^c = (S^c, \sim^c_i : i \in N), \{R^c_G : \emptyset \neq G \subseteq N\}, E^c, V^c)\) for \(CLD\) is defined as follows:
\begin{itemize}
  \item \(S^c\) is the set of maximal consistent sets.
  \item \(s \sim^c_i t\) iff \(K_a s = K_a t\)
  \item \(sR_G t\) iff \(D_H s = D_H t\) whenever \(H \subseteq G\)
  \item \(V^c(p) = \{s \in S^c : p \in s\}\)
  \item \(X \in E^c(G)(s)\) iff \[
  \begin{cases}
  \exists \phi \{s \in S^c : \phi \in s\} \subseteq X : [G] \phi \in s & G \neq N \\
  \forall \phi \{s \in S^c : \phi \in s\} \subseteq S^c \setminus X : [\emptyset] \phi \notin s & G = N
  \end{cases}
  \]
\end{itemize}

\begin{lemma}[Pseudo Truth Lemma]
\(M^c, s \models \phi \iff \phi \in s\).
\end{lemma}

\begin{proof}
The proof is by induction on \(\phi\). The epistemic cases are exactly as for standard normal modal logic. The case for coalition operators is exactly as in [11].
\end{proof}
It is easy to check that $\sim^c_i$ are equivalence relations and E1-E5 hold for $E^c$.

**Lemma 4 (Finite Pseudomodel)** Every CLD-consistent formula $\phi$ has a finite pseudomodel where E1-E6 hold.

**Proof** The proof is exactly as in Theorem 1, namely the construction of $M_f$, but starting with a Canonical Playable Pseudomodel rather than Canonical Playable Model; the definition of $M^c$ contains the clause

$$\Gamma R_G \Delta \text{ iff } \forall H \subseteq G \{ \psi : D_H \psi \in \Gamma \} = \{ \psi : D_H \psi \in \Delta \}$$

We add the following condition to the closure: $D_i \phi \in cl(\phi)$ iff $K_i \psi \in cl(\phi)$. We define $M_f$ to be a pseudomodel instead of a model, by adding the clause:

$$[s]R^f_G [s'] \text{ iff } \forall H \subseteq G \{ \psi : D_H \psi \in [s] \} = \{ \psi : D_H \psi \in [s'] \}$$

We show that $M_f$ is indeed a pseudomodel:

1. $R^f_i = \sim^f_i$: this follows from the fact that $K_i \phi \in [s]$ iff $D_i \phi \in [s]$ for any $i, \phi$ and $s$, which holds because of the $K_i \phi \rightarrow D_i \phi$ axiom and the new closure condition above.
2. $G \subseteq H \Rightarrow R^f_H \subseteq R^f_G$: this holds by definition.

We add a case for $\theta = D_G \psi$ to the inductive proof. This case is proven in exactly the same way as the $\theta = K_i \psi$ case: the definitions of $\sim^f_i$ and $R^f_G$ are of exactly the same form (in particular, $R^f_G$ is also an $S5$ modality). The proof that E1-E6 hold in the resulting pseudomodel is the same as in the proof of Theorem 1 for $E^f$.

We are now going to transform the pseudomodel into a proper model; it is a well-known technique for dealing with distributed knowledge. In fact, we can make direct use of a corresponding existing result for epistemic logic with distributed knowledge, and extend it with the coalition operators/effectivity functions. We here give the more general result for the language with also common knowledge, which will be useful later.

**Theorem 2 ([5])** If $M = (S, \{ \sim_i : i \in N \}, \{ R_G : \emptyset \neq G \subseteq N \}, V)$ is an epistemic pseudomodel, then there is an epistemic model $M' = (S', \{ \sim'_i : i \in N \}, V')$ and a surjective (onto) function $f : S' \rightarrow S$ such that for every $s' \in S'$ and formula $\phi \in ELCD$, $M, f(s') \models \phi$ iff $M', s' \models \phi$.

**Proof** This result is directly obtained from the completeness proof for $ELCD$ sketched in [5] p. 70. For a more detailed proof (for a more general language), see [14] Theorem 9. 

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**Theorem 3** If a formula is satisfied in a finite pseudomodel, then it is satisfied in a model.

**Proof** Let $M = (S, \{\sim_i : i \in N\}, \{R_G : G \neq N\}, E, V)$ be a finite pseudomodel such that $M, s \models \phi$. Let $M_p = (S, \{\sim_i : i \in N\}, \{R_G : G \neq N\}, V)$ be the epistemic pseudomodel underlying $M$, and let $M_p' = (S', \{\sim'_i : i \in N\}, V')$ and $f : S' \rightarrow S$ be as in Theorem 2. Let $\text{image}(X) = \{s' : f(s') \in X\}$ for any set $X \subseteq S$. Finally, let $M' = (S', \{\sim'_i : i \in N\}, E', V')$ where $E'$ is defined as follows:

- For $G \neq N$:
  \[ Y \in E'(G)(u) \iff \exists X \subseteq S, (Y \supseteq \text{image}(X) \text{and } X \in E(G)(f(u))) \]

- for $G = N$:
  \[ Y \in E'(G)(u) \iff \bar{X} \notin E'((\emptyset)(u)) \]

Two things must be shown: that $M'$ is a proper model, and that it satisfies $\phi$.

Since $M_p'$ is an epistemic model, to show that $M'$ is a model all that remains to be shown is that $E'$ is truly playable. We now show that that follows from true playability of $E$.

**E1** Note that $\text{image}(X) = \emptyset$ iff $X = \emptyset$.

For $G \neq N$, $\emptyset \in E'(G)(u)$ iff (by definition of $E'$) $\exists X \subseteq S, s \in S (\emptyset \supseteq \text{image}(X) \text{and } X \in E(G)(f(u)))$ which is impossible since $M$ satisfies E1. Note that in particular this proves $\emptyset \notin E'(\emptyset)(u)$.

For $N$, $\emptyset \in E'(N)(u)$ iff $S' \neq E'(\emptyset)(u)$ and we’ll see that this is impossible below.

**E2** Note that $\text{image}(S) = S'$.

For $G \neq N$, $S' \in E'(G)(u)$ iff (by definition of $E'$) $\exists X \subseteq S, (S' \supseteq \text{image}(X) \text{and } X \in E(G)(f(u)))$ and since $S' \supseteq \text{image}(S)$ and $S \in E(G)(f(u))$, $S' \in E'(G)(u)$ holds. Note that in particular this proves $S' \in E'(\emptyset)(u)$.

For $N$, $S' \in E'(N)(u)$ iff $\emptyset \notin E'(\emptyset)(u)$ and this was proved above.

**E3** $\forall u \in S' \forall Y \subseteq S', \bar{Y} \notin E'(\emptyset)(u) \Rightarrow Y \in E'(N)(u)$ follows immediately from the definition for $E'(N)$.

**E4** $E'$ is monotonic by definition for $G \neq N$.

For $N$, assume $X \subseteq Y$ and $X \in E'(N)(u)$. Then $\bar{X} \notin E'(\emptyset)(u)$. Since for $\emptyset$ we already have monotonicity and $\bar{Y} \subseteq \bar{X}, \bar{Y} \notin E'(\emptyset)(u)$.

So $Y \in E'(N)(u)$.
∀u ∈ S′ ∨ G_1, G_2 ⊆ N \forall X′, Y′ ⊆ S′ X′ ∈ E′(G_1)(u) and Y′ ∈ E′(G_2)(u) \Rightarrow X′ \cap Y′ ∈ E′(G_1 ∪ G_2)(u), where G_1 ∩ G_2 = ∅

For G_1, G_2 ≠ N:

Let s = f(u), G_1 ∩ G_2 = ∅, X′ ∈ E′(G_1)(u), Y′ ∈ E′(G_2)(u). This means that for some X, Y, such that X′ ⊇ X and Y′ ⊇ Y, X ∈ E(G_1)(s) and Y ∈ E(G_2)(s), so since M satisfies E5, X ∩ Y ∈ E(G_1 ∪ G_2)(s). Since X′ ⊇ X and Y′ ⊇ Y, X′ ∩ Y′ ⊇ X ∩ Y, so X′ ∩ Y′ ∈ E′(G_1 ∪ G_2)(u).

For G_1 = N (G_2 has to be ∅): X′ ∈ E′(N)(u), Y′ ∈ E′(∅)(u), prove X′ ∩ Y′ ∈ E′(N)(u). We have X′ ̸∈ E′(∅)(u), Y′ ∈ E′(∅)(u). Assume by contradiction X′ ∩ Y′ ̸∈ E′(N)(u), then X′ ∩ Y′ ∈ E′(∅)(u) which means X′ ∩ Y′ ∈ E′(∅)(u). This together with Y′ ∈ E′(∅)(u) and E5 for G_1, G_2 = ∅ gives (X′ ∪ Y′) ∩ Y′ ∈ E′(∅)(u), that is X′ ∈ E′(∅)(u). The latter contradicts X′ ̸∈ E′(∅)(u).

E6 Suppose X ∈ E′ nc(∅)(s). We claim that for every u such that s = f(u), \text{image}(X) ∈ E′ nc(∅)(u).

Assume by contradiction that there exists a Y ⊆ \text{image}(X) such that Y ∈ E′ nc(∅)(u) for some u s.t. s = f(u). By the definition of E′, this means that there is a Z such that \text{image}(Z) ⊆ Y and Z ∈ E(∅)(s).

Since Y ⊆ \text{image}(X) and \text{image}(Z) ⊆ Y it follows that \text{image}(Z) ⊆ \text{image}(X). But it is a property of the \text{image} function that that implies that Z ⊆ Y, and this contradicts the assumption that Z ∈ E(∅)(s) and X ∈ E′ nc(∅)(s).

In order to show that M′ satisfies φ, we show that M, f(u) \models γ if M′, u \models γ for u ∈ S′ and any γ, by induction in γ. All cases except γ = [G]φ are exactly as in the proof of Theorem 2[see [14] Theorem 9] for a detailed inductive proof.

For the case that γ = [G]φ, the inductive hypothesis is that for all ψ with |ψ| < |[G]φ|, and any t, v with t = f(v), M, t \models ψ iff M′, v \models ψ. Given that for every v there is a unique t such that t = f(v), we can state this as \{v: M′, v \models ψ\} = \text{image}(ψM), or ψM′ = \text{image}(ψM).

First consider G ≠ N. M, s \models [G]φ iff φM ∈ E(G)(s). Consider \text{image}(φM).

By the inductive hypothesis, φM = \text{image}(φM). φM ∈ E(G)(s) holds iff φM′ ∈ E′(G)(u) iff M′, u \models [G]φ.

M, s \models [N]φ iff φM ∈ E(N)(s) iff (as above) -φM′ \notin E′(∅)(u) iff M′, u \models [N]φ.

Explanation of (•): one direction E3, the other direction E5 and E1.

Corollary 2 For any CLD-formula φ, \vdash_{CLD} φ iff \models φ.

5 Completeness of Coalition Logic with both Common and Distributed Knowledge

In this section we consider the logic \textit{CLCD}, extending coalition logic with operators for individual knowledge, common knowledge and distributed knowledge.
The axiomatisation $CLCD$ is shown in Figure 4. It extends $CL$ with standard axioms and rules for individual, common and distributed knowledge.

As usual, soundness can easily be shown.

**Lemma 5 (Soundness)** For any $CLCD$-formula $\phi$, $\vdash_{CLCD} \phi \Rightarrow |\phi| = \phi$.

In the remainder of this section we show that $CLCD$ also is complete.

**Theorem 4** Any $CLCD$-consistent formula is satisfied in a finite pseudomodel.

**Proof** The proof is identical to the proof of Lemma 4, with the addition of the inductive clause $\theta = C_G \psi$ as in the proof of Theorem 1.

We can now use the same approach as in the case of $CLD$.

**Theorem 5** If a $CLCD$ formula is satisfied in a finite pseudomodel, it is satisfied in a model.

**Proof** The proof goes exactly like the proof of Theorem 3, using Theorem 2. The definition of the model $M'$ is identical to the definition in Theorem 3 as is the proof that it is a proper model. For the last part of the proof, i.e., showing that $M'$ satisfies $\phi$, note that the last clause in Theorem 2 holds for epistemic logic with both distributed and common knowledge. Thus, the proof is completed by only adding the inductive clause for $[G] \phi$, which is done in exactly the same way as in Theorem 3.

**Corollary 3** For any $CLCD$-formula $\phi$, $\vdash_{CLCD} \phi$ iff $|\phi| = \phi$.

### 6 Conclusions

This paper solves several hitherto open problems, namely proving completeness of Coalition Logic extended with group knowledge modalities. The axioms for the epistemic modalities are the same as in the absence of the Coalition Logic axioms, however the completeness proofs require non-trivial combinations of techniques. The next step would be to look at complete axiomatisations of logics resulting from imposing some conditions on the interaction of coalitional ability and group knowledge (such as the examples in the Introduction), and obtaining results on the complexity of satisfiability problem for $CLC$, $CLD$ and $CLCD$.

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Prop Classical propositional logic

G1 \(\neg [G] \bot\)
G2 \([G] \top\)
G3 \(\neg [\emptyset] \phi \to [N] \phi\)
G4 \([G] (\phi \land \psi) \to [G] \psi\)
G5 \([G_1] \phi \land [G_2] \psi \to [G_1 \cup G_2] (\phi \land \psi)\), if \(G_1 \cap G_2 = \emptyset\)

MP \(\vdash_{CLD} \phi, \phi \to \psi \implies \vdash_{CLD} \psi\)
RG \(\vdash_{CLD} \phi \leftrightarrow \psi \implies \vdash_{CLD} [G] \phi \leftrightarrow [G] \psi\)
K \(K_i (\phi \to \psi) \to (K_i \phi \to K_i \psi)\)
T \(K_i \phi \to \phi\)
4 \(K_i \phi \to K_i K_i \phi\)
5 \(\neg K_i \phi \to K_i \neg K_i \phi\)
RN \(\vdash_{CLD} \phi \implies \vdash_{CLD} K_i \phi\)
DK \(D_G (\phi \to \psi) \to (D_G \phi \to D_G \psi)\)
DT \(D_G \phi \to \phi\)
D4 \(D_G \phi \to D_G D_G \phi\)
D5 \(\neg D_G \phi \to D_G \neg D_G \phi\)
D1 \(K_i \phi \leftrightarrow D_i \phi\)
D2 \(D_G \phi \to D_H \phi\), if \(G \subseteq H\)

Figure 3: CLD: axiomatisation of CLD.
**Prop** Classical propositional logic

G1 \neg [G] \perp

G2 [G] \top

G3 \neg [\emptyset] \neg \phi \rightarrow [N] \phi

G4 [G](\phi \land \psi) \rightarrow [G] \psi

G5 [G_1] \phi \land [G_2] \psi \rightarrow [G_1 \cup G_2](\phi \land \psi), \text{ if } G_1 \cap G_2 = \emptyset

MP \vdash_{\mathcal{L}CD} \phi, \phi \rightarrow \psi \Rightarrow \vdash_{\mathcal{L}CD} \psi

RG \vdash_{\mathcal{L}CD} \phi \leftrightarrow \psi \Rightarrow \vdash_{\mathcal{L}CD} [G] \phi \leftrightarrow [G] \psi

K \ K_i(\phi \rightarrow \psi) \rightarrow (K_i \phi \rightarrow K_i \psi)

T \ K_i \phi \rightarrow \phi

4 \ K_i \phi \rightarrow K_i K_i \phi

5 \ \neg K_i \phi \rightarrow K_i \neg K_i \phi

RN \vdash_{\mathcal{L}CD} \phi \Rightarrow \vdash_{\mathcal{L}CD} K_i \phi

C1 \ E_G \phi \leftrightarrow \bigwedge_{i \in G} K_i \phi

C2 \ C_G \phi \rightarrow E_G(\phi \land C_G \phi)

RN \vdash_{\mathcal{L}CD} \phi \Rightarrow \vdash_{\mathcal{L}CD} K_i \phi

RC \vdash_{\mathcal{L}CD} \phi \rightarrow E_G(\phi \land \psi) \Rightarrow \vdash_{\mathcal{L}CD} \phi \rightarrow C_G \psi

DK \ D_G(\phi \rightarrow \psi) \rightarrow (D_G \phi \rightarrow D_G \psi)

DT \ D_G \phi \rightarrow \phi

D4 \ D_G \phi \rightarrow D_G D_G \phi

D5 \ \neg D_G \phi \rightarrow D_G \neg D_G \phi

D1 \ K_i \phi \leftrightarrow D_i \phi

D2 \ D_G \phi \rightarrow D_H \phi, \text{ if } G \subseteq H

Figure 4: \mathcal{L}CD: axiomatisation of \mathcal{L}CD.