Calibrating Expressiveness of Collective Notions

Barbara Dunin-Kęplicz

Warsaw University and Polish Academy of Sciences

Based on work with Rineke Verbrugge

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Motivations

A modern perspective of collective activity

- autonomous, intelligent cooperative systems
- teamwork (or Cooperative Distributed Problem Solving) as a paradigmatic activity
- spectacular and complex patterns of interaction

The objective

- to isolate the essential aspects of collective behavior
- to (possibly separately) characterize them
- to construct expressive enough, still possibly minimal formal model of collective behavior

A compromise between abstract model and reality is to be reached.
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Circumstances of collective behavior vary significantly w.r.t.:

- topological structure of groups (societies)
- power relations
- communication medium

Collective aspects need to be studied in detail each and every time when tailoring a model for a specific application.

Goal:

to diversify the expressive power of modeled notions, including formal mechanisms to calibrate their expressiveness.
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- agents of many different sorts (e.g. software agents, robots, UAV’s: unmanned aerial vehicles)
- working together, but also with humans
- in an unstable and unpredictable environment

BGI (or BDI: beliefs, desires, intentions) systems

Our focus on mental state of cooperating participants

- beliefs (informational aspect)
- goals
- intentions (motivational aspect)
**BGI model of agency**

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Informational attitudes

[Fagin, Halpern, Moses, Vardi] [Meyer, Van der Hoek]

Individual belief

- **$\text{BEL}(i, \varphi)$**: agent $i$ believes $\varphi$

General belief

- Notation: $G$ – a group
- **$\text{E-BEL}_G(\varphi)$**: each agent in group $G$ believes $\varphi$

Common belief

- **$\text{C-BEL}_G(\varphi)$**: everyone in $G$ believes $\varphi$, everyone in $G$ believes that everyone in $G$ believes $\varphi$, etc.
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Modal operators for group beliefs

Axioms & rule

- \(KD45_n^C\) is the modal system \(KD45_n\) plus:
- \(E-BEL_G(\varphi) \leftrightarrow \bigwedge_{i \in G} \text{BEL}(i, \varphi)\)
- \(C-BEL_G(\varphi) \rightarrow E-BEL_G(\varphi \land C-BEL_G(\varphi))\)
- From \(\varphi \rightarrow E-BEL_G(\psi \land \varphi)\) infer \(\varphi \rightarrow C-BEL_G(\psi)\) (Induction Rule).

\(C-BEL_G(\psi)\) is easy to understand, hard to achieve.
Established by *communication + reasoning*
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Different degrees of belief in group

[Parikh, Krasucki]

\[ \text{BEL}(\psi), \text{E-BEL}_G(\psi), \text{E-BEL}^2_G(\psi), \ldots, \text{C-BEL}_G(\psi) \]

For teamwork, \( \text{E-BEL}_G(\psi) \) is not sufficient: \( \text{C-BEL}_G(\psi) \) needed.

Important to realize

- How wide is the spectrum of possibilities to express knowledge/beliefs of agents and teams?
- How frequently we use models of others in our everyday commonsense reasoning?
- How important in modern intelligent systems is to create and/or revise models of others’ minds and reason about them?
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From our experience in modeling group behavior

- Crucial: to differentiate the scope and strength of group attitudes.
- The resulting characteristics may differ significantly, and even become logically incomparable.

Agents’ awareness forms the main difference over various contexts of common activity

Awareness about the situation: the state of agent’s:
- beliefs about itself
- beliefs about other agents
- beliefs about the environment

Various epistemic notions: from distributed beliefs to common knowledge are adequate to formalize agents’ awareness
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Awareness in teamwork

The question

- *who* needs to know *what* in order to cooperate effectively?

Tuning awareness

- possibly minimal solution per context is searched (communication and reasoning necessary for higher levels of awareness are costly and complex)
- awareness of different aspects should be tuned separately

Outcome

A sort of logical *tuning mechanism*.
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**Group**

A group is a system of agents that are somehow constrained in their mutual interactions. [Weiss]

**Team**

A team is a group in which the agents are restricted to having a common goal of some sort. [Weiss]

**From group to team**

Joint intention by a team does not consist merely of simultaneous and coordinated individual actions; to act together, a team must be aware of and care about the status of the group effort as a whole [Levesque et al.]
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Bratman’s theory

Future-directed intentions

- can **not** be reduced to desires (goals) and beliefs
- have to do with partial plans and enable intra- and interpersonal coordination

Intentions play an important role in practical reasoning

- drive means-end reasoning
- constrain future deliberation
- persist
- influence beliefs upon which future practical reasoning is based
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**TeamLog**, a theory of teamwork

a theory of motivational attitudes of cooperating agents.

- **TeamLog** is founded on individual and social attitudes.
- **TeamLog** addresses a nontrivial problem of group attitudes: collective intention and collective commitment.
- Collective notions are tuned to circumstances and organizational structure of the team.
- Agents reason about mental attitudes of others.
- In applications, assumptions regarding others are kept to a minimum (to avoid overthinking and assure flexibility.)
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Collective intentions in strictly cooperative groups

Postulates for a collective intention

Again, \( \varphi \): the goal of the system.

- All members of the group *individually intend* \( \varphi \): a general intention \( M\text{-INT}_G(\varphi) \)
- All members in the group *intend* other members intend \( \varphi \), etc.: a mutual intention \( M\text{-INT}_G(\varphi) \) (a motivational core of group intention expressing reciprocity).
- Group members are aware about this mutual intention.

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Axioms for mutual and collective intention

- **E-INT}_G(\varphi)**: “every agent in \( G \) intends \( \varphi \)”.
- \( KD45^M-INT}_G \) is the modal system \( KD45 \) plus:
  - \( E-INT}_G(\varphi) \leftrightarrow \bigwedge_{i \in G} INT(i, \varphi) \)
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  - From \( \varphi \rightarrow E-INT}_G(\psi \land \varphi) \) infer \( \varphi \rightarrow M-INT}_G(\psi) \) (Induction Rule).

**Definition of collective intention**

\[ C-INT}_G(\varphi) \leftrightarrow M-INT}_G(\varphi) \land \text{awareness}_G(M-INT}_G(\varphi)) \]
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Example of a collective intention

- Two violinists, $a$ and $b$, have studied together and toyed with the idea of giving a concert together someday.
- Later this becomes more concrete: $\text{INT}(a, \varphi)$ and $\text{INT}(b, \varphi)$, where $\varphi = “a$ and $b$ perform the solo parts of the Bach Double Concerto”.
- After communicating with each other about this, they start practising together. A mutual intention $\text{M-INT}_G(\varphi)$ is now in place for $G = \{a, b\}$, plus a collective belief about this, so $\text{C-INT}_G(\varphi)$.
- An opportunity appears: Carnegie Hall plans a concert for Christmas Eve, including the Bach Double Concerto.
Example of a collective intention cntd.

- Now \(a, b\) refine their collective intention to \(C-\text{INT}_G(\psi)\), where \(\psi = \text{“}a\text{ and }b\text{ perform the solo parts of the Bach Double Concerto at the Christmas Eve concert in Carnegie Hall”}\).

- \(a, b\) are chosen to be the soloists, and both sign the appropriate contract. Because they do this together, they have common knowledge, not merely collective belief, of their mutual intention: \(M-\text{INT}_G(\psi) \land C-\text{KNOW}_G(M-\text{INT}_G(\psi))\).

- Common knowledge can be justified if needed, and a commonly signed contract provides a perfect basis for this.

\(a, b\) have developed a very strong variant of collective intention.
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Collective commitment in TeamLog

Collective commitment
- the *key* concept in TeamLog
- subject to calibration: various building blocks tuned separately

Subjects related to agents’ autonomy
- collective responsibility
- collective decision making
- collective planing
- collective revision making
- hiding classified issues
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The distinction de dicto vs. de re

- \( \bigwedge \bigvee_{\alpha \in \mathcal{P}} \bigvee_{i,j \in \mathcal{G}} \text{C-BEL}_G(\text{COMM}(i,j,\alpha)) \) — detailed awareness

- \( \text{C-BEL}_G(\bigwedge \bigvee_{\alpha \in \mathcal{P}} \bigwedge_{i,j \in \mathcal{G}} \text{COMM}(i,j,\alpha)) \) — global awareness
TeamLog’s complexity

**Complexity**

- The key notions are highly complex infinite concepts: its satisfiability problem is $\text{ExpTime}$-complete.
- Domain-specific knowledge helps to tailor TeamLog to the circumstances, reducing the complexity by applying weaker forms of awareness.
Team structure

- **coordinator** – coordinates teamwork between subteams of $G$.
- Helicopter with a *pilot* – directly accountable to the coordinator, communicates as equal with the UAVs.
- Several subteams $G_1, \ldots, G_k \subseteq G$ work in parallel. Each of these subteams $G_i$ consists of:
  - $UAV_i$ – responsible for assigned sectors
  - $n_i$ identical robots $rob_{i1}, \ldots, rob_{in_i}$ – responsible to their $UAV_i$. 
Team hierarchy

- Coordinator
- Direction of hierarchy
- UAV_1
- UAV_k
- Pilot
- G_1
- G_k
- rob_{1,1}
- rob_{1,n_1}
- rob_{k_1}
- rob_{k,n_k}
Adjusting collective intention to the case-study

Robots – two cases
1. Only individual actions are performed.
2. Limited form of cooperation: teams of two robots.

Robots – two cases for intentions
1. A general intention $E\text{-INT}_G$ about the goals is enough.
2. $E\text{-INT}^2_G$ is enough to form two-robot teams that are not competitive internally!
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Robots: minimal levels of awareness and group intention

Robots – two cases for beliefs

1. General belief about every group intention
   \( \text{E-BEL}_G(\text{E-INT}_G(\varphi)) \).  

2. \( \text{E-BEL}_G^2 \) suffices to allow deliberation about other robots’ intentions and beliefs, especially \( \text{E-BEL}_G^2(\text{E-INT}_G^2(\varphi)) \).
The **UAVs** – two cases for intentions

Within the team **UAV** must make sure that all agents are motivated to do their tasks.

1. \( \text{INT}(\text{UAV}, \text{E-INT}_G(\varphi)) \) is required w.r.t. the subteam group intention \( \text{E-INT}_G(\varphi) \).

2. \( \text{INT}(\text{UAV}, \text{E-INT}^2_G(\varphi)) \) is required w.r.t. the level of subteam group intention \( \text{E-INT}^2_G(\varphi) \).

The **UAVs** – beliefs

For **UAVs** to work with each other, they need at least \( \text{E-BEL}^2_G \) of other **UAVs’** intentions.
**UAV**: minimal levels of awareness and group intention

**The UAVs – two cases for intentions**

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Coordinator: minimal levels of awareness and group intention

The coordinator – intentions
Similarly, one level of intention more than the UAVs suffices to ensure the proper level of motivations:
\[ \text{INT}(\text{coordinator}, \text{INT}^2_G(\varphi)). \]

The coordinator – beliefs
The coordinator sees the team as a collection of cooperating subteams: Therefore
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Substantial question
To what extend cognitive science can help in these issues?
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Another possibility to calibrate collective concepts

Graded concepts

• In BGI graded concepts express e.g.
  • the strength of beliefs
  • the importance of goals
  • the degree of commitment to intentions.

• By reinterpreting beliefs, goals and intentions and then group attitudes, a graded version of TEAMLOG has been constructed [Dunin-Kęplicz, Nguyen and Szałas]
Lowering the complexity of reasoning

**Reasoning via querying deductive/knowledge databases**

The tradeoff:
- complexity of computing queries
- expressiveness of query language

A candidate rule query language: 4QL (http://4ql.org)
- 4QL [Małuszyński and Szałas] is a general purpose DATALOG rule language
- 4QL addresses lack of knowledge and inconsistencies
- 4QL has \( \text{PTIME} \) data complexity and captures \( \text{PTIME} \)

A shift from the multimodal BGI model to a 4QL-based BGI model
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