Paraconsistent Distributed Belief Fusion

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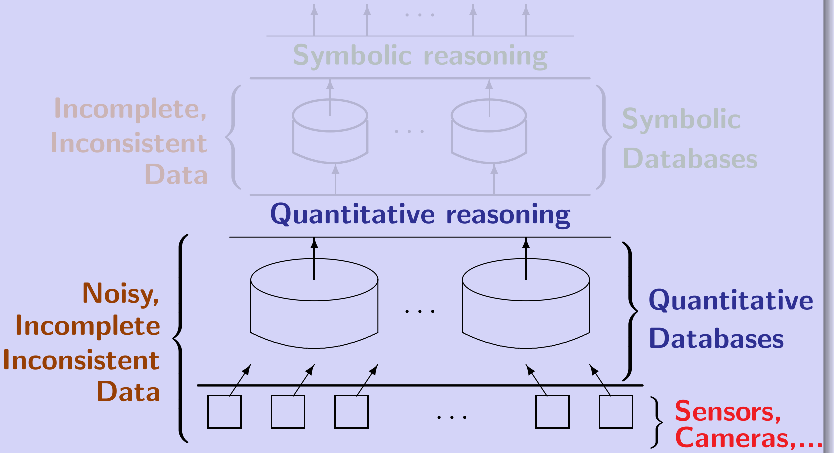
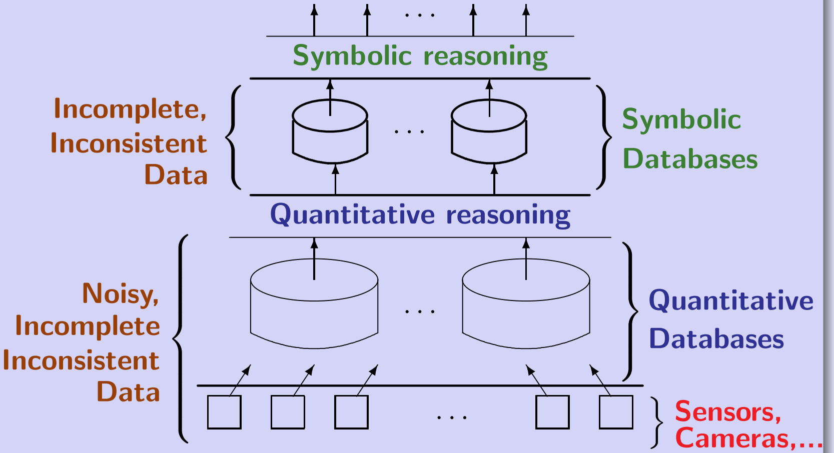
Agent's Reasoning




Symbolic reasoning
Incomplete, Inconsistent Data
Symbolic Databases
Quantitative reasoning
Noisy, Incomplete Inconsistent Data
Quantitative Databases
Sensors, Cameras,...

Issues

- Initial and intermediate beliefs are confronted with other beliefs originating from a variety of sources.
- Final beliefs can substantially deviate from the initial ones.
- After belief formation there might still exist areas of agents' ignorance and inconsistencies.
- Knowledge representation techniques reflecting commonsense (nonmonotonic) reasoning are desirable.

Our Postulates

- Despite partially unsettled information, agents need to make individual or collective decisions and act accordingly.
- A variety of reasoning methods should support the reduction of agents' ignorance and inconsistencies.
- The framework should allow for highly distributed processing, in particular reflecting the agents' and groups' organizational structures.

Contribution of the Paper

- A practical model of distributed belief fusion.
- Implementation framework via epistemic profiles.
- Tractability of the method.
- Paraconsistent models allowing for inconsistencies and lack of information.
- Incorporating lightweight versions of nonmonotonic reasoning techniques.

Semantical Structures

Reflect the processes of agent's belief acquisition and formation:

- an agent starts with *constituents*: sets of beliefs acquired by perception, expert supplied knowledge, communication, etc.
- next, the constituents are transformed into *consequents* according to agent's *individual epistemic profile*,
- *derivatives*: sets of intermediate beliefs supporting implementation of epistemic profiles in a distributed manner.

The Novelty of the Framework

Individual vs Group Level

- Conceptual compatibility between individuals and groups.
- Consequents of group members become constituents at the group level.
- Constituents are further transformed into group consequents via groups' epistemic profiles.

Uniformity

The same uniform approach applies to groups of groups of agents or to mixed groups of individuals and other complex topologies.

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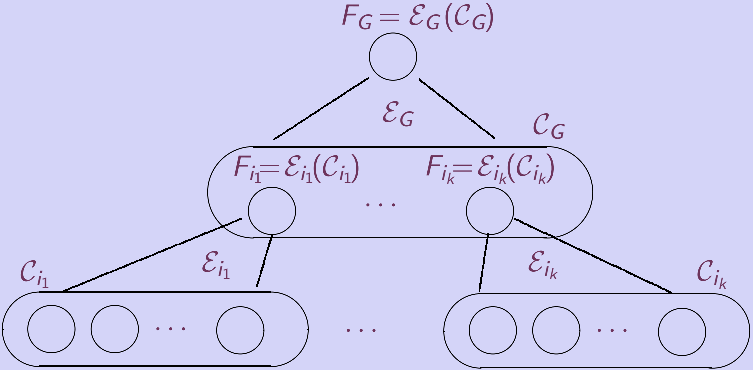
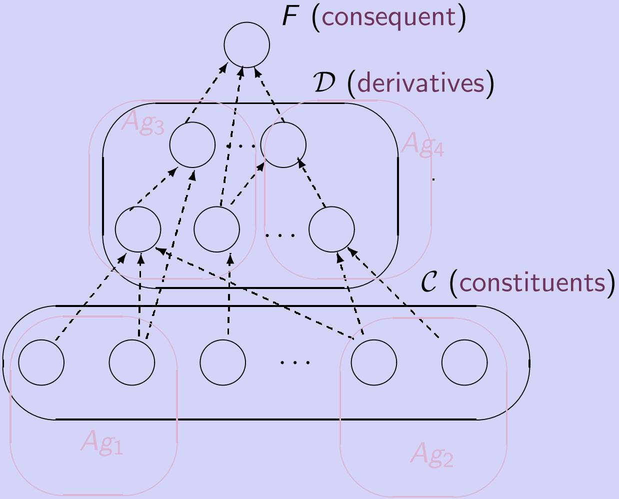
Definition

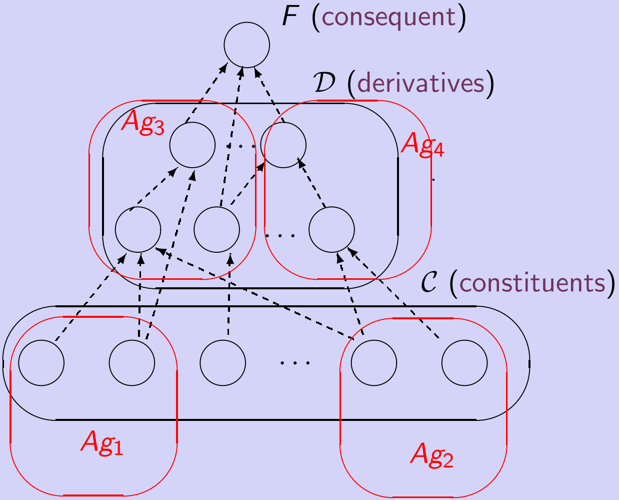
Let $\mathbb{C} \stackrel{\text{def}}{=} \textsc{Fin}(\mathcal{G}(\text{Const}))$ be the set of all finite sets of ground literals over the set of constants Const. Then:

- by a *constituent* we understand any set $C \in \mathbb{C}$;
- by an *epistemic profile* we understand any function $\mathcal{E} : \textsc{Fin}(\mathbb{C}) \longrightarrow \mathbb{C}$;
- by a *belief structure over an epistemic profile* $\mathcal{E}$ we mean $\mathcal{B}^{\mathcal{E}} = \langle \mathcal{C}, F \rangle$, where: $\mathcal{C} \subseteq \mathbb{C}$ is a nonempty set of constituents; $F \stackrel{\text{def}}{=} \mathcal{E}(\mathcal{C})$ is the *consequent* of $\mathcal{B}^{\mathcal{E}}$.

Individual and Group Belief Structures




F (consequent)
$\mathcal{D}$ (derivatives)
$\mathcal{C}$ (constituents)
Ag_3
Ag_4
Ag_1
Ag_2



F (consequent)
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Ag_2

The Scenario

An agent is equipped with:

- a sensor platform for detecting air pollution;
- two different sensors for measuring the noise level.

The agent has also information about places in the neighborhood, etc.

The Task

Decide whether conditions in the considered location are healthy.

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The Task

Decide whether conditions in the considered location are healthy.

Constituents

- C_p gathers beliefs about air pollution at given places. $P(x, y)$ indicates the pollution level y at place x, where $y \in \{low, moderate, high\}$;
- C_n gathers beliefs about noise level at given places. $N_i(x, y)$ indicates the noise level y at place x, as measured by a sensor $i \in \{1, 2\}$, where $y \in \{low, moderate, high\}$;
- C_e gathers information about the environment. $Cl(x, y)$ indicates that place x is close to a place characterized by y, where $y \in \{pollutive, noisy, neutral\}$.

Exemplary Constituents

$$C_p = \{P(a, low)\}$$
$$C_n = \{N_1(a, high)\}$$
$$C_e = \{\neg Cl(a, noisy), Cl(a, neutral), Cl(a, pollutive)\}$$

An Example – continued

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Exemplary Derivatives

- D_p – for deciding the pollution level;
- D_n – for deciding the noise level.

Such derivatives may be:

$$D_p = \{P(a, moderate)\},$$
$$D_n = \{N(a, high)\}.$$

Exemplary Consequents

Based on constituents and derivatives, the agent has to decide whether the situation is healthy.

The agent may accept an inconsistent consequent:

$$F = \{\neg S(a, healthy), S(a, healthy)\}.$$

Syntax

- Classical first-order language over a given vocabulary without function symbols.
- $\mathrm{Bel}_i()$, $\mathrm{Bel}_G()$ standing for individual and group beliefs.

Semantics

Substantially differs from the classical one:

- truth values $\mathfrak{t}, \mathfrak{i}, \mathfrak{u}, \mathfrak{f}$ (true, inconsistent, unknown, false) are explicitly present (natural for modeling many potentially distributed information sources);
- is based on sets of ground literals.

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Definition

The *truth value* of a literal ℓ w.r.t. a set of ground literals L and valuation v, denoted by $\ell(L, v)$, is defined as follows:

$$\ell(L, v) \stackrel{\text{def}}{=} \begin{cases} \mathfrak{t} & \text{if } \ell(v) \in L \text{ and } (\neg\ell(v)) \notin L; \\ \mathfrak{i} & \text{if } \ell(v) \in L \text{ and } (\neg\ell(v)) \in L; \\ \mathfrak{u} & \text{if } \ell(v) \notin L \text{ and } (\neg\ell(v)) \notin L; \\ \mathfrak{f} & \text{if } \ell(v) \notin L \text{ and } (\neg\ell(v)) \in L. \end{cases}$$

4QL (see 4ql.org)

- Possibly many, perhaps distributed information sources.
- Four logical values ($\mathfrak{t}$, $\mathfrak{f}$, $\mathfrak{i}$, $\mathfrak{u}$).
- Introduces simple tools: rules, modules and external literals to formulate and enrich (lightweight versions of) (Local) Closed World Assumption, autoepistemic reasoning, default reasoning, defeasible reasoning, etc.
- Deterministic polynomial time complexity of computing queries.
- Captures all tractable queries.

Experimental open source interpreter Inter4QL can be downloaded from 4ql.org.

Exemplary Nonmonotonic Rules for Derivatives

module Dp:
  rules:
    P(X, moderate) :– Cp.P(X, low) IN {TRUE, INCONS},
        Ce.Cl(X, pollutive) IN {TRUE, UNKNOWN}.
    ...
end.

module Dn:
  rules:
    N(X,Y) :– Cn.N1(X,Y), Cn.N2(X,Y) IN {TRUE, UNKNOWN} |
        Cn.N1(X,Y) IN {TRUE, UNKNOWN}, *Cn.N2(X,Y).*
    ...
end.

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...

end.

Exemplary 4QL Rules

Exemplary Nonmonotonic Rules for Consequents

module F:

rules:

$$
\begin{array}{lcl}
-\,S(X, \mathit{healthy}) & :- & Dn.N1(X, \mathit{high}), Dn.N2(X, \mathit{high}). \\
S(X, \mathit{healthy}) & :- & Cp.P(X, \mathit{moderate}), \\
 & & Cn.N1(X, \mathit{low}) \text{ IN } \{\text{TRUE}, \text{UNKNOWN}\}.
\end{array}
$$

...

end.

Conclusions

- Belief structures and epistemic profiles reflect agents' and groups' reasoning capabilities.
- Components of belief structures can naturally be distributed among agents, groups of agents, etc.
- The framework supports distributed individual and group belief fusion.
- Handling inconsistencies and gaps in beliefs is supported by paraconsistent and nonmonotonic reasoning.
- 4QL is a tool to implement all epistemic profiles and belief structures constructible in deterministic polynomial time.