Inconsistency Management for Traffic Regulations

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Inconsistency Management for Traffic Regulations

- **Traffic regulation**: Legal document, describing how road usage can be restricted (for reasons of safety, trafficability, ...)

- **Traffic measures** describe what *shall* be restricted

- **Traffic signs** (and road markings) describe what *is* restricted

- Measures and signs are two different “languages” for the description of restrictions, which shall correspond

- E.g.: Speed limit, parking ban, residential area, pedestrian zone, motorway, one way streets, mandatory turns,...
Example: Inconsistent traffic sign posting

Scenario: Speed limit measure of 30 mph from $v_2$ to $y_2$ (→→)

correct sign posting
Example: Inconsistent traffic sign posting

Scenario: Speed limit measure of 30 mph from $v_2$ to $y_2$ (→→)

Inconsistencies:
- no end sign at $y_1$
- speed limit ending at $y_2$ does not start
Example: Loop

Scenario: Four mandatory left turns cause a loop
Traffic regulation data management

- Industrial project at PRISMA solutions GmbH
  (http://www.prisma-solutions.at): Web app for administration of traffic measures/signs on a digital street map
- Government officials collect data, store and visualize
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- Government officials collect data, store and visualize
- Status quo: system users detect faults manually
- Problems: legal issues, errors in data acquisition
- Goal: provide assistance w.r.t. consistency-related problems (detect, diagnose and repair inconsistencies)
Traffic regulation data management (ctd.)

- Logic-based approach for street maps (labeled, directed graphs)
  - logical formulas for expressing traffic regulation specifications
  - Represent measures and signs by edge/node labels
  - Translate into “effects” (i.e., a common language)
  - Evaluate by additional formulas, potentially creating “conflicts”
  - Inconsistency, if a conflicts can be derived
- Leave open which logic is used

T. Krennwallner (Vienna UT) Inconsistency Mgmt. for Traffic Regulations Semantic Cities @ AAAI’12
Traffic Regulation: Informal questions

- **Consistency**: Given a set of measures and/or signs on a street, are they *consistent* (w.r.t. the traffic regulation)?

- **Correspondence**: Do measures and signs express the same “effects,” i.e., are the restrictions described by measures properly materialized by the traffic signs?

- **Diagnosis**: Which minimal set of measures/signs explain inconsistency or non-correspondence?

- **Repair**: Which minimal changes to the scenario can resolve these problems?
High-level approach

- **Scenario** $Sc = (G, M, S)$, using atoms over a logic $\mathcal{L}$:
  - Directed, labeled graph $G$, representing street map
  - Set of atoms: measures $M$ and signs $S$, using nodes from $G$
  - Input $I = M \cup S$

- Traffic regulatory specification split up into two sets of logical formulas, applied in two steps:
  - (i) **Effect mapping**: from signs and measures to effects $F$
  - (ii) **Conflict specification**: from effects to conflicts $C$

- Intuitively: $(G, I) \xrightarrow{(i)} (G, F) \xrightarrow{(ii)} (G, C)$

- $\Rightarrow$ Basis for definition of reasoning tasks
Street map, Effects, and Conflicts

- Edge direction: possible direction of traffic
- Edge labels: *left* and *right* (turn), *straight*, *u-turn*, *lane*
- Represented as atoms, e.g., \( e(\text{left}, x, y) \)
- Map measures and signs to a “common target language” of effects \( f \) (e.g., first-order logic)

Example (Effects and Conflicts)

- speed limit measure of \( k \) mph on edge \((x, y)\) \(\mapsto\) maximal allowed speed \(k \) mph: \( \forall k, x, y . m(spl(k), x, y) \supset f(maxspeed(k), x, y) \)

- \( k \) mph start sign on node \( x \) \(\mapsto\) maximal allowed speed \(k \) mph on next lane: \( \forall k, x, y . s(spl\text{-start}(k), x) \land e(lane, x, y) \supset f(maxspeed(k), x, y) \)

- conflicts are defined by mapping effects to conflicts:
  \( \forall k, j, x, y . f(maxspeed(k), x, y) \land f(maxspeed(j), x, y) \land k \neq j \supset c(\text{ambig-max-speed}, x, y) \)
Mappings: Effects & Conflicts

- Let $\mathcal{L}$ be a predicate logic, $X$ and $Y$ sets of ground atoms

- Closed world operator on $X$ relative to (implicit) base set $Y \supseteq X$:
  \[
  \overline{X} = X \cup \{ \neg x \mid x \in Y \setminus X \}.
  \]

- The $Y$-consequences of theory $T$ and $X$ (on $G$) is the set of atoms
  \[
  Cn_G(T, X, Y) = \{ y \in Y \mid T \cup \overline{G} \cup \overline{X} \models y \}.
  \]

- We make two (sequential) applications of this operator to obtain
  - effects from measures and signs, and then, in case of inconsistency,
  - conflicts from effects
Mappings: Effects & Conflicts (ctd.)

Recall: \( Cn_G(T, X, Y) = \{ y \in Y \mid T \cup \overline{G} \cup \overline{X} \models y \} \)

\( I_G/F_G/C_G \): set of all possible inputs (measures & signs)/effects/conflicts

**Definition (Effects)**

An **effect mapping** is a set \( P \) of formulas over \( \mathcal{L} \) that associates with each input \( I \subseteq I_G \) on a street map \( G \) the set

\[
\mathcal{F}^P_G(I) = Cn_G(P, I, F_G)
\]

of atoms, called **effects of** \( I \) **(on** \( G \) **).**

**Definition (Conflicts)**

A **conflict specification** over an effect mapping \( P \) is a set \( Sp \) of formulas over \( \mathcal{L} \) that associates with each input \( I \subseteq I_G \) on a street map \( G \) the set

\[
C_G^{P,Sp}(I) = Cn_G(Sp, \mathcal{F}^P_G(I), C_G)
\]

of atoms, called **conflicts of** \( I \) **(on** \( G \) **).**
Traffic Regulation Problems and Consistency

**Definition (Traffic Regulation Problem)**

Let $Sp$ be a conflict specification over an effect mapping $P$, and $Sc = (G, M, S)$ be a scenario. Then, the pair $\Pi = (Sp, P)$ is called a traffic regulation and the pair $T = (\Pi, Sc)$ a traffic regulation problem.

**Definition (Conflicts/Consistency of Traffic Regulation Problems)**

The conflicts $C(T)$ of a traffic regulation problem $T$ are defined as the set of conflict atoms derived by the subsequent application of these two mappings on its scenario, i.e., $C(T) = C_{G,Sp}(I)$. If $C(T) \neq \emptyset$, we call $T$ inconsistent.

**Reasoning task CONS**

Decide whether a given traffic regulation problem $T$ is consistent.
Diagnosis

Definition (Diagnosis)

Given a set of conflicts $C \subseteq C(T)$, a diagnosis for $C$ is a (minimal) set $J \subseteq I$, s.t. $C \subseteq C_G^{P,Sp}(J)$.

Reasoning task UMINDIAG

Decide whether conflicts $C \subseteq C(T)$ have a unique $\subseteq$-minimal diagnosis.

Example

The measure ($\rightarrow$) assigned to the edge $(y_1, y_2)$ is the diagnosis of the conflict at $y_1$ (no 30 kmph start sign at $y_1$).
Correspondence

Definition

A set of measures $M$ and a set of signs $S$ correspond wrt. $P$ and $G$, if $F_P^G(M) = F_P^G(S)$, i.e., if the effects of $M$ and $S$ on $G$ coincide.

Reasoning task CORR

Given $M$ and $S$, decide whether $F_P^G(M) = F_P^G(S)$, i.e., whether

Repair

Recall: $I = M \cup S$, $I_G$ are all possible measures and signs on $G$

Definition

A repair for an inconsistent $\mathcal{T}$ is a pair $(I^-, I^+)$, where

- $I^- \subseteq I$
- $I^+ \subseteq I_G \setminus I$
- $C_{G}^{P,Sp}((I \setminus I^-) \cup I^+) = \emptyset$.

That is, $(I^-, I^+)$ is a repair, if the scenario obtained by deleting measures/signs $I^-$ and adding $I^+$ is consistent.

Reasoning task REPAIR

Decide for a given (inconsistent) $\mathcal{T}$ whether some admissible repair exists, i.e., some $I^+, I^- \subseteq I_G$ s.t. $C_{G}^{P,Sp}((I \setminus I^-) \cup I^+) = \emptyset$ and a poly-time admissibility predicate $\mathcal{A}(I^+, I^-)$ holds.
### Complexity of Reasoning Tasks

<table>
<thead>
<tr>
<th>Logic $\mathcal{L}$</th>
<th>IMPL</th>
<th>CONS</th>
<th>CORR</th>
<th>UMinDiag</th>
<th>REPAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>FO+DCA</td>
<td>co-NExp / PSpace</td>
<td></td>
<td></td>
<td>$P_{np}^\text{Exp} / \text{PSpace}$</td>
<td>$\text{NP}_{np}^\text{Exp} / \text{PSpace}$</td>
</tr>
<tr>
<td>ASP$^\neg_s$</td>
<td>Exp / $P_{np}$</td>
<td>Exp / $P_{np}$</td>
<td></td>
<td>Exp / in $P_{\Sigma_p^2}$, $\Pi_p^2$-hard</td>
<td>Exp / $\Sigma_p^2$</td>
</tr>
<tr>
<td>ASP$^\neg$</td>
<td>co-NExp / $\Pi_p^2$</td>
<td>$P_{np}^\text{Exp} / \text{P}_{\Sigma_p^2}$</td>
<td></td>
<td>$P_{np}^\text{Exp} / \text{in} P_{\Sigma_p^3}$, $\Pi_p^3$-hard</td>
<td>$\text{NP}_{np}^\text{Exp} / \Sigma_p^3$</td>
</tr>
<tr>
<td>ASP$^\lor,\neg$</td>
<td>co-NExp$^\text{NP}$ / $\Pi_p^3$</td>
<td>$P_{np}^\text{Exp}^\text{NP} / \text{P}_{\Sigma_p^3}$</td>
<td></td>
<td>$P_{np}^\text{Exp}^\text{NP} / \text{in} P_{\Sigma_p^4}$, $\Pi_p^4$-hard</td>
<td>$\text{NP}_{np}^\text{Exp}^\text{NP} / \Sigma_p^4$</td>
</tr>
</tbody>
</table>

Legenda: general case / bounded predicate arities (unless stated otherwise, entries are completeness results)

- **IMPL**: Known logical entailment complexities
- **FO+DCA**: first order logic with domain closure assumption
- **ASP$^\neg_s$**: stratified answer set programs
- **ASP$^\neg$**: normal programs (arbitrary negation)
- **ASP$^\lor,\neg$**: disjunctive programs (arbitrary disjunction and negation)
Implementation of the Reasoning Tasks

- Prototype implementation based on Answer Set Programs, using \texttt{dlv} and \texttt{clasp} as solvers.
- Uniform encoding for all reasoning tasks
- Traffic regulation as sets of rules
- Input: Facts encoding the street graph, traffic measures & signs
- Output: Answer sets that correspond to conflicts/diagnoses/repairs

Example

- Graph: \texttt{edge(right,x2,y1). edge(straight,v3,y1)}.
- Measures: \texttt{m(spl(30),v2,v3). m(motorway,x42,x43)}.
- Signs: \texttt{s(start(spl(30)),v2). s(no_entry,x19)}. 
Implementation CONS

- Measure & signs: function symbols \( x \in \{ m, s \} \):
  - input(\( x (...) \)). measure/sign is given as input
  - pool(\( x (...) \)). measure/sign is in pool (for guessing)
  - use(\( x (...) \)). measure/sign is used

- Only the effects of *used* measures & signs are computed

- Reasoning task CONS (via conflict evaluation): use entire input:
  - use(\( x (...) \)) :- input(\( x (...) \)).

- Scenario is consistent iff answer set does not contain a conflict.
Implementation DIAGNOSIS

▶ Guess:

\[
\text{pool}(x(...)) \leftarrow \text{input}(x(...)). \\
\text{use}(x(...)) \lor \neg\text{use}(x(...)) \leftarrow \text{pool}(x(...)).
\]

▶ Modifications:

\[
\text{keep}(x(...)) \leftarrow \text{use}(x(...)), \quad \text{input}(x(...)). \\
\text{del}(x(...)) \leftarrow \neg\text{use}(x(...)), \quad \text{input}(x(...)). \\
\text{add}(x(...)) \leftarrow \text{use}(x(...)), \neg\text{input}(x(...)).
\]

▶ Preferred answer sets w.r.t. an optimization criterion using weak constraints (second rule below)

▶ Diagnosis:

\[
\leftarrow \text{add}(x(...)). \quad \% \text{adding not allowed} \\
\sim \text{keep}(x(...)). \quad \% \text{keep as few as possible}
\]
Implementation REPAIR

▶ A repair shall be able to add new measures and signs

▶ Adding new measures/signs to the pool based on domain knowledge, e.g.,
  ▶ If there is a measure \( m(T, X, Y) \) in the pool, add a start sign at \( X \) and an end sign at \( Y \) to the pool.

\[
\text{pool}(s(\text{start}(T), X)) :- \text{pool}(m(T, X, Y)).
\]
\[
\text{pool}(s(\text{end}(T), Y)) :- \text{pool}(m(T, X, Y)).
\]

▶ Repair (example preference):

\[
\text{:- conf.} \quad \text{% forbid any conflict}
\]
\[
\sim \text{del}(s(T, X)). \quad [1:1] \text{% prefer changes of signs } [:1]
\]
\[
\sim \text{add}(s(T, X)). \quad [2:1] \text{% over measures [:2]},
\]
\[
\sim \text{del}(m(T, X, Y)). \quad [1:2] \text{% then deletions } [1:],
\]
\[
\sim \text{add}(m(T, X, Y)). \quad [2:2] \text{% over additions } [2:].
\]

▶ \text{dlv} optimizes hierarchically: \( \sim \text{<body>} \). [\text{Weight:Level}]
Conclusion

Inconsistency Management for Traffic Regulation

- Introduced traffic regulation problem and relevant reasoning tasks
- Presented logic-based, modular approach
- Complexity results for different logics
- Prototypical implementation using answer set programming

Future work

- Extend existing industrial software using presented features
- Test on real world data, scaling issues
- Consider additional plate information (for whom or when a measure/sign is active)
Diagnosis (Side remark)

Different domain interpretations are reasonable:

- Before the end sign, the speed limit effect is given by measure, but not by a sign.

- Q: Is the end sign ending an effect, i.e., is the conflict “No effect to be ended here?” appropriate at the position of the end sign?

- Modular, declarative implementation needed accounting for this flexibility.
Adjustment & Generation

- Restricted scenarios / restricting repairs lead to special cases, relevant for data imports and merging.
- **Adjustment** of signs, s.t. they correspond with measures. Amounts to finding a repair consisting exclusively of traffic signs. (Recall 30 kmph example.)
- **Generation** of signs from scratch, s.t. they correspond with measures. Corresponds to a repair \((\emptyset, I^+)\) on scenario \((G, M, \emptyset)\), where \(I^+\) consists exclusively of signs.

Example (encoding of special domain knowledge)

- Favor changes in signs over changes in measures
- Favor deletions of linear measures over zones
- Never delete a residential area
- ...
Relationship to Abductive Diagnoses

Abductive diagnosis [Poole, 1989] and [Console and Torasso, 2006].

Definition (Abductive Diagnosis Problem)

An *abductive diagnosis problem (ADP)* is a triple $\langle T, H, O \rangle$, where $T$ is a set of formulas in $\mathcal{L}$, called the theory, and $H$ and $O$ are sets of literals, called the hypotheses and observations, respectively.

A *(complete)* abductive diagnosis for $\langle T, H, O \rangle$ is a set $A \subseteq H$, such that $T \cup \overline{A} \not\models \bot$ and $T \cup \overline{A} \models O$.

Proposition

Let $C \subseteq C(\mathcal{T})$ and $J \subseteq I$. The effects $\mathcal{F}^P_G(J)$ are an abductive diagnosis for the ADP $\langle Sp \cup \overline{G}, \mathcal{F}^P_G(I), C \rangle$ iff $J$ is a consistent diagnosis of $C$, i.e., $Sp \cup \overline{G} \cup \overline{\mathcal{F}^P_G(J)} \not\models \bot$. 
References I
