Automating Signature Evolution
in Logical Theories

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Outline

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Appropriate representation is the key to successful problem solving.

No representation is a complete description of the world. *So, representations must change as problems and environments change.*

Cannot pre-align representations of large, diverse agent communities. *So, autonomous agents must realign their representations automatically and dynamically.*

Both *signatures* and beliefs must be fluent.
Multi-agent world: offering and using services.

Plans consist of sequence of such services.

Plans may fail during execution.

Fault diagnosis identifies mismatch between ontologies.

Repair mechanism changes planning agent’s ontology.

- Split or merge predicates
- Add or remove arguments of predicates
- Add or remove preconditions of planning operators

Re-plan with new ontology (maybe recursively).

Successfully evaluated on sequences of KIF and Planet ontologies.
Issues with ORS

- Needed ontology development history for evaluation.
  - Sequences of ontology versions hard to obtain.
  - For those we have, rationale of diagnosis and repair incomplete.
- Search arises from diagnosis/repair choices as well as inference.
- Representational refinements incompletely defined.
  - Splitting a function: which new function replaces each occurrence of an old one?
  - Adding an argument: what values should its occurrences take?
Addressing these Issues

- Lots of well documented case studies in physics domain.
- *Ontology repair plans* control search.
- Plans complete refinement definitions.
- Multiple contexts facilitate targetted repairs.
Ontology Repair Plans

- Aggregate atomic operations into ontology repair plans.
  - Atomic operations: split/combine functions, add/remove arguments, etc.
  - Trigger formula signals applicability and instantiates plan.
  - Repairs change both beliefs and signature.
  - Multiple contexts used in both trigger and repair.

- The *Where’s My Stuff* ontology repair plan.
  - Triggered by conflict between predicted and observed values of stuff.
  - Splits old stuff into visible, invisible and total stuff.

- The *Inconstancy* ontology repair plan.
  - Triggered by conflict between predicted independence and observed dependence.
  - Adds this dependency as new argument to stuff.
The **GALILEO System**

- Implemented both repair plans in **GALILEO** system in $\lambda$Prolog.
  - Guided Analyses of Logical Inconsistencies Leads to Evolved Ontologies.
- Higher-order logic needed at both object- and meta-level.
- Polymorphism required to ensure generality of plans.
- Successfully tested on some development examples.
- Will build larger test set for evaluation.
- Will develop, implement and evaluate further repair plans.
The Where’s My Stuff Ontology Repair Plan

Trigger

\[ O_t \vdash stuff(\vec{s}) = v_1, \quad O_s \vdash stuff(\vec{s}) \approx v_2, \quad O_t \vdash v_1 > v_2 \]

Split stuff

\[ \forall \vec{s} : \vec{\tau}. stuff_{invis}(\vec{s}) ::= stuff(\vec{s}) - stuff_{vis}(\vec{s}) \]

Create new axioms

\[ Ax(\nu(O_t)) ::= \{ \forall \vec{s} : \vec{\tau}. stuff_{invis}(\vec{s}) ::= stuff(\vec{s}) - stuff_{vis}(\vec{s}) \} \]
\[ \cup Ax(O_t) \]
\[ Ax(\nu(O_s)) ::= \{ \phi\{stuff / stuff_{vis}\} \mid \phi \in Ax(O_s) \} \]
Before Joseph Black’s investigations, heat and temperature conflated.

Leads to paradox when heat is reduced but temperature is constant!

Latent heat: the (hidden) heat energy involved in the phase change of a substance.
### Application to the Latent-Heat Paradox

#### Example

**Original ontologies:**

\[
\begin{align*}
O_t & \vdash \text{Heat}(H_2O, \text{Start(Freeze)}) = \text{Heat}(H_2O, \text{Start(Freeze)}) \\
O_s & \vdash \text{Heat}(H_2O, \text{Start(Freeze)}) \approx \text{Heat}(H_2O, \text{End(Freeze)}) \\
O_t & \vdash \text{Heat}(H_2O, \text{Start(Freeze)}) > \text{Heat}(H_2O, \text{End(Freeze)})
\end{align*}
\]

**Substitution:**

\[
\{ \text{Heat}/\text{stuff}, \langle H_2O, \text{Start(Freeze)} \rangle/\vec{s}, \text{Heat}(H_2O, \text{Start(Freeze)})/\nu_1, \text{Heat}(H_2O, \text{End(Freeze)})/\nu_2 \}
\]

**Splitting stuff:**

\[
\forall o : \text{obj}, t : \text{mom}. \ \text{LHF}(o, t) ::= \text{Heat}(o, t) - \text{Temp}(o, t)
\]

**Repaired ontologies:**

\[
\begin{align*}
\nu(O_t) & \vdash \text{Heat}(H_2O, \text{Start(Freeze)}) > \text{Heat}(H_2O, \text{End(Freeze)}) \\
\nu(O_s) & \vdash \text{Temp}(H_2O, \text{Start(Freeze)}) \approx \text{Temp}(H_2O, \text{End(Freeze)})
\end{align*}
\]
Paradox of the Bouncing Ball

diSessa experiment on physics students.

Initially, ball has potential, but no kinetic energy.

Just before contact, ball has kinetic, but no potential energy.

*Where is energy at point of contact?*

In deformation of ball.

- Need to idealise ball with extent.
Application to the Bouncing-Ball Paradox

Example

Original ontologies:

\[ O_t \vdash TE(Ball, End(Drop)) = TE(Ball, Start(Drop)) \]
\[ O_s \vdash TE(Ball, End(Drop)) \approx 0 \]
\[ O_t \vdash TE(Ball, Start(Drop)) > 0 \]

Substitution: \{ \(TE / \text{stuff}, \langle Ball, End(Drop)\rangle / \bar{c}, \ TE(Ball, Start(Drop))/v_1, \ 0/v_2\} \]

Splitting stuff: \( \forall o:obj, \ t:tmom. \ TE(o, t) ::= TE_{\text{part}}(o, t) + EE(o, t) \)

Repaired ontologies:

\[ \nu(O_t) \vdash TE(Ball, End(Drop)) = TE(Ball, Start(Drop)) \]
\[ \nu(O_s) \vdash TE_{\text{part}}(Ball, End(Drop)) \approx 0 \]
Dark Matter

- Newtonian mechanics can predict relationship between orbital velocity and radius of stars.
- But actual relationship is different!
- Dark matter: some invisible matter surrounding the visible matter in a halo.
Application to the Discovery of Dark Matter

Example

Original ontologies:

\[ O_t \vdash \lambda s \in \text{Spiral}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle = \text{Graph}_p \]
\[ O_s \vdash \lambda s \in \text{Spiral}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle \approx \text{Graph}_a \]
\[ O_t \vdash \text{Graph}_p < \text{Graph}_a \]

Substitution: \{\lambda s \in g. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle / \text{stuff}, \langle \text{Spiral} \rangle / \bar{s}, \text{Graph}_p / v_1, \text{Graph}_a / v_2 \}

Splitting stuff:

\[ \lambda s \in \text{Spiral}_{\text{invis}}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle \]
\[ ::= \lambda s \in \text{Spiral}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle \]
\[ - \lambda s \in \text{Spiral}_{\text{vis}}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle \]

Repaired ontologies:

\[ \nu(O_t) \vdash \lambda s \in \text{Spiral}_{\text{vis}}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle = \text{Graph}_p \]
\[ \nu(O_s) \vdash \lambda s \in \text{Spiral}. \langle \text{Rad}(s), \text{Orb}_\text{Vel}(s) \rangle \approx \text{Graph}_a \]
Anomaly of Precession of Perihelion of Mercury

- Newtonian mechanics predicts that planetart orbits precess.
- But prediction for Mercury is wrong.
- Additional planet (Vulcan) would account for discrepancy.
Application to the Precession of the Perihelion of Mercury

Example

Original ontologies:

\[ \nu(O_t) \vdash \lambda o \in \text{Solar\_System}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle = M2O^{-1}(\text{Orbit}_p) \]
\[ \nu(O_s) \vdash \lambda o \in \text{Solar\_System}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle \approx M2O^{-1}(\text{Orbit}_o) \]
\[ \nu(O_t) \vdash M2O^{-1}(\text{Orbit}_p) < M2O^{-1}(\text{Orbit}_o) \]

Substitution:

\{ \lambda o \in s, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle / \text{stuff}, \langle \text{Solar\_System} \rangle / \vec{c}, M2O^{-1}(\text{Orbit}_p) / \nu_1, M2O^{-1}(\text{Orbit}_o) / \nu_2 \}

Splitting stuff:

\[ \nu(O_t) \vdash \lambda o \in \text{Solar\_System}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle \]
\[ := \lambda o \in \text{Solar\_System}_{vis}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle \]
\[ + \lambda o \in \text{Solar\_System}_{invis}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle \]

Repaired ontologies:

\[ \nu(O_t) \vdash \lambda o \in \text{Solar\_System}_{vis}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle = M2O^{-1}(\text{Orbit}_p) \]
\[ \nu(O_s) \vdash \lambda o \in \text{Solar\_System}, t. \langle \text{Posn}(o, t), \text{Mass}(o) \rangle \approx M2O^{-1}(\text{Orbit}_o) \]
The Inconstancy Ontology Repair Plan

**Trigger**

- $O_t \vdash stuff(\bar{x}) ::= c(\bar{x})$
- $O_s(V(\bar{s}, \bar{b}_1) = v_1) \vdash stuff(\bar{s}) \approx c_1(\bar{s})$
- $\exists i \neq j. O_t \vdash c_i(\bar{s}) \neq c_j(\bar{s})$
- $O_s(V(\bar{s}, \bar{b}_n) = v_n) \vdash stuff(\bar{s}) \approx c_n(\bar{s})$

**Add variad**

- $\nu(stuff) ::= \lambda \bar{y}, \bar{x}. F(c(\bar{x}), V(\bar{x}, \bar{y}))$

**Create new axioms**

- $Ax(\nu(O_t)) ::= \{ \phi\{stuff / \nu(stuff)(\bar{y})\} \mid \phi \in Ax(O_t) \}$
- $\setminus \{ stuff(\bar{x}) ::= c(\bar{x}) \}$
- $\cup \{ \nu(stuff) ::= \lambda \bar{y}, \bar{x}. F(c(\bar{x}), V(\bar{x}, \bar{y})) \}$
- $Ax(\nu(O_s(V(\bar{s}, \bar{b}_i) = v_i))) ::= \{ \phi\{stuff / \nu(stuff)(\bar{b}_i)\} \mid \phi \in Ax(O_s(V(\bar{s}, \bar{b}_i) = v_i)) \}$
Newtonian theory of gravity predicted that objects further out will have lower velocities.

The observed velocities of those objects are almost constant!

MOND - The gravitational ‘constant’ is not constant at low accelerations.
Application to MOND

Example

Original ontologies:

\[ O_t \vdash G := 6.67 \times 10^{-11} \]

\[ O_s(\text{Acc}(S_1) = A_1) \vdash G \approx M2OV^{-1}(OV(S_1), \text{Mass}(S_1), \lambda s \in \text{Spiral} \setminus \{S_1\}. \langle \text{Posn}(s), \text{Mass}(s) \rangle) (= G_1) \]

\[ \vdots \]

\[ O_s(\text{Acc}(S_n) = A_n) \vdash G \approx M2OV^{-1}(OV(S_n), \text{Mass}(S_n), \lambda s \in \text{Spiral} \setminus \{S_n\}. \langle \text{Posn}(s), \text{Mass}(s) \rangle) (= G_n) \]

\[ \exists i \neq j.\ O_t \vdash G_i \neq G_j \]

Substitution: \{G/stuff, \langle\rangle/\tilde{\langle\rangle}, \langle\rangle/\bar{\langle\rangle}, 6.67 \times 10^{-11}/c, \text{Acc}/V, \langle S_i \rangle/\check{b}_i, G_1/c_1, G_n/c_n\}

New Definition: \( \nu(G) := \lambda s. F(6.67 \times 10^{-11}, \text{Acc}(s)) \)

Repaired ontologies:

\[ \nu(O_t) \vdash \nu(G) := \lambda s. F(6.67 \times 10^{-11}, \text{Acc}(s)) \]

\[ \nu(O_s(\text{Acc}(S_1) = A_1)) \vdash \nu(G)(S_1) \approx M2OV^{-1}(OV(S_1), \text{Mass}(S_1), \lambda s \in \text{Spiral} \setminus \{S_1\}. \langle \text{Posn}(s), \text{Mass}(s) \rangle) (= G_1) \]

\[ \vdots \]

\[ \nu(O_s(\text{Acc}(S_n) = A_n)) \vdash \nu(G)(S_n) \approx M2OV^{-1}(OV(S_n), \text{Mass}(S_n), \lambda s \in \text{Spiral} \setminus \{S_n\}. \langle \text{Posn}(s), \text{Mass}(s) \rangle) (= G_n) \]
Boyle’s law states that, at a fixed temperature, the pressure and the volume of a gas are inversely proportional, i.e.
\[ \text{pressure} \times \text{volume} = k \]

The ideal gas law: \[ \text{pressure} \times \text{volume} = k \times \text{temperature} \]
Application to Boyle’s Law

Example

Original ontologies:

\[ O_t \vdash Boyle(gas) ::= \lambda\text{mom}. \; P(\text{gas, mom}) \times V(\text{gas, mom}) = K(\text{gas}) \]

\[ O_s(T(Gas, Mom_1) = T_1) \vdash Boyle(Gas) \approx P(Gas, Mom_1) \times V(Gas, Mom_1) (= K_1) \]

\[ \vdots \]

\[ O_s(T(Gas, Mom_n) = T_n) \vdash Boyle(Gas) \approx P(Gas, Mom_n) \times V(Gas, Mom_n) (= K_n) \]

\[ \exists i \neq j. \; O_t \vdash K_i \neq K_j \]

Substitution: \{Boyle/stuff, \langle Gas\rangle/s, \langle gas\rangle/x, K/c, T/V, \langle Mom_i\rangle/\vec{b}_i, K_1/c_1, K_n/c_n\}

New Definition: \( \nu(Boyle) ::= \lambda\text{mom, gas}. \; F(K(gas), T(gas, mom)) \)

Repaired ontologies:

\[ \nu(O_t) \vdash \nu(Boyle) ::= \lambda\text{mom, gas}. \; F(K(\text{gas}), T(\text{gas, mom})) \]

\[ \nu(O_s(T(Gas, Mom_1) = T_1)) \vdash (\nu(Boyle)(\text{Mom}_1))(\text{Gas}) \approx P(\text{Gas, Mom}_1) \times V(\text{Gas, Mom}_1) (= K_1) \]

\[ \vdots \]

\[ \nu(O_s(T(Gas, Mom_n) = T_n)) \vdash (\nu(Boyle)(\text{Mom}_n))(\text{Gas}) \approx P(\text{Gas, Mom}_n) \times V(\text{Gas, Mom}_n) (= K_n) \]
Conservative Extensions and Minimal Repairs

- Want repairs to be minimal.
- Adapt conservative extension.

\[
\phi \in \text{Sig}(O) \implies (\nu(O) \vdash \nu(\phi) \iff O \vdash \phi)
\]

- In WMS, both \(\nu(O_t)\) and \(\nu(O_s)\) are conservative in this sense.

\[
\text{Ax}(\nu(O_t)) := \{\forall \vec{s} : \vec{r}. \text{stuff} \sigma_{\text{invis}}(\vec{s}) := \text{stuff}(\vec{s}) - \text{stuff} \sigma_{\text{vis}}(\vec{s})\}
\]

\[
\cup \text{Ax}(O_t)
\]

\[
\text{Ax}(\nu(O_s)) := \{\phi\{\text{stuff} / \text{stuff} \sigma_{\text{vis}}\} | \phi \in \text{Ax}(O_s)\}
\]

- The combined ontologies are not conservative.
- Situation more complicated for Inconstancy.
Multiple Contexts

Why have separate theoretical and sensory ontologies?

- Enables control over contradiction.
- Focuses effect of repair operations.
- Allows use of conservative extension to show minimality.
Research Programme

- Discovery, analysis and formalisation of physics case studies: both development and test sets.
- Development of physics ontologies: before and after repair.
- Development of a theory of ontology evolution.
- Development of a few, generic ontology repair plans.
  - Merging functions, drop arguments, apply analogy, uncaused causes, etc.
- Implementation and evaluation of these repair plans.
Ontology evolution is a key technology for adaptive, autonomous agents.

Physics is good development domain because of historical record.

Higher-order logic needed at object- and meta-levels.

Repair plans address problems of search and ambiguity.

Developed and tested two repair plans so far.

Implemented in λProlog GALILEO system.