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GALILEO: A System for Automating Ontology Evolution

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Abstract
We describe the GALILEO system, which is designed for automating the evolution of higher-order logic ontologies by incorporating user interaction for diagnosing and repairing faults. In particular, we present our approach to ontological conflict diagnosis, which circumvents problems posed by HOL’s undecidability by means of: formalising modular ontologies as Isabelle locales and preparing the system by user interaction; applying ontology repair plans and automatically identifying logically valid terms that are responsible for the conflict; and, automatically eliminating physically meaningless terms.

1 Introduction
The process of revising an ontology in the face of new information is key to many areas of Computer Science. The literature on the subject calls such processes ontology evolution and concentrates on how Description Logic (DL) ontologies for Semantic Web applications need to evolve in order to maintain their coherence and consistency (ontology debugging) or relative to other ontologies (ontology alignment). We decided to investigate ontology evolution by formalizing and automating in higher-order logic (HOL) the mechanisms to repair locally consistent but possibly globally inconsistent ontologies, i.e. ontologies that are individually consistent but may give rise to an inconsistency when merged. Working with locally consistent ontologies enables the reasoning about the shape of the cause of the global conflict, allowing for specific meaningful repairs. The notion of ontologies we adopted is a general one, i.e. a specification of a conceptualisation [Gruber, 1993], which is compatible with our treatment of HOL theories as ontologies. Unlike the less expressive logics, including DL, our approach naturally allows for the formalisation of ontology evolution both as belief revision and syntactic manipulation (e.g., splitting a function, changing its arity, etc.). HOL has proven advantageous in at least three other ways. Firstly, HOL’s polymorphism of variables (and other symbols such as ≤, ≥, +, −, etc.) permits the generality of the proposed repair plans for evolution and their applicability over diverse cases. Secondly, HOL-based theorem provers, such as Isabelle, enable HO-reasoning for ontology evolution and reasoning over locally consistent but globally inconsistent ontologies that share variables. Finally, many complex concepts are better represented as HOL objects, e.g., the orbit of a star – this is relevant because the examples used for developing and testing GALILEO are based on the evolution of physics, which involves concepts best represented as functions. This, therefore, relates our work to scientific discovery [Langley, 1981].

In this paper, we provide an overview of the GALILEO system, which is the first system to attempt to automate ontology evolution in HOL. In particular, we present our approach to ontological conflict diagnosis, which circumvents problems posed by HOL’s undecidability by means of: a) formalising modular ontologies as locales [Ballarin, 2006] and preparing the system by user interaction; b) automatically identifying logically valid terms that are responsible for the conflict; and, c) automatically eliminating physically meaningless terms. We have designed mechanisms called ontology repair plans (ORPs) [Bundy and Chan, 2008], each of which defines a trigger pattern for detecting that certain faults exist in the given ontologies and a set of transformation rules for resolving the detected conflict. The identification of the term that gives rise to the inconsistency, hereafter designated by “conflict term” and the variable stuff, underpins the diagnosis component and is a relatively complex reasoning task – whereas the repair component typically involves relatively simple syntactic manipulation of the ontologies based on the result of the diagnosis. Thus, in this paper, we present only GALILEO’s diagnosis component and briefly outline the repair.

2 Case Study and Ontology Repair Plans
We describe below the running example for the rest of the paper: the contradiction between the predicted and the observed orbital velocity of galaxies. We then describe two ORPs, which can be applied to resolve the conflict that underlies the case study and produce two different but historically proposed explanations.
2.1 Case Study: Predicted vs. Observed Orbital Velocity of Galaxies

Newtonian dynamics predicts that orbital velocities\(^1\) of stars in a spiral galaxy decrease inversely with the square root of the distance from the galactic centre, or the radius. However, the velocity observed was almost constant out to large radii (Figure 1), as first observed by Rubin [Rubin et al., 1980]. One explanation is about the theoretical existence of dark matter, which is matter that is inferred to exist in the universe but not give off light, and is based on various sources of evidence, including the fact that the observed orbital velocities of stars in spiral galaxies exceeds the predicted values. Rubin concluded that some invisible matter is exerting a gravitational force on these stars, causing the unexpectedly high velocities.

Suppose the contradiction arises from observing the galaxy rotation curves \(Ga\) and \(Gb\) of type \(Gly \rightarrow Real \rightarrow Real\), which are the curves based on prediction and observation, respectively, where \(Gly\) is the type of galaxy. Let the ontology of the predictive theory \(Thy\) contain definitions, including that of orbital velocity, and assertions about the value of various properties of different stars; let the sensory ontology, \(Sens\), contain observations made on the rotational velocity of a galaxy, as reported in [Rubin et al., 1980]. Figure 2 highlights some of the axioms available in the two ontologies, where \(Evt\), \(Gly\), \(Dst\), and \(Str\) denote types for representing events, galaxies, distances, and stars, respectively; \(G\) denotes the universal gravitational constant; \(OV\), the orbital velocity; \(gr\), the set of stars in the galaxy \(g\) up to the radius \(r\); \(M\), the mass of a body; \(Rad\), the radius of a star from its galactic centre; \(RtV\), the rotational velocity; \(RdV\), the radial velocity; \(SyV\), the velocity of the galactic system relative to the observer; \(Inc\), the inclination of the galaxy; \(\lambda Shift\), the shift in wave length; \(Gly1\), the galaxy being observed; \(Star1\) and \(Star2\), stars in the observed galaxy; and, \(Obs6\), the observation event.

Note that the graph object in (1) is defined using equality on functions, whereas that in (4) is defined using the equality

\[ Ax(Thy) := \{ \forall e: Evt.Ga(Gly1) := OV(e, Gly1) \} \]
\[ \forall e: Evt, \ g: Gly, \ r: Dst. \ OV(e, g) := \]
\[ \sqrt{\frac{G \times \sum s \in gr.M(e, s)}{r}}, \ G := 6.67 \times 10^{-11}, \]
\[ M(Obs6, Star1) := 5, \ M(Obs6, Star2) := 9 \ldots \} \]
\[ Ax(Sens) := \{ \forall s: Str. \]
\[ Gb(Gly1, Rad(s, Gly1)) := \]
\[ RtV(Obs6, s, Gly1), \]
\[ \forall e: Evt, \ s: Str, \ g: Gly. \ RtV(e, s, g) := \]
\[ RdV(e, s, g) - SyV(e, g) \]
\[ \frac{\sin(Inc(e, g))}{\lambda Shift(Obs6, Star1, Gly1, \ldots) = 300, \ldots} \]

Figure 1: The \(x\)-axis is the distance of the stars in the galaxy \(Gly1\) from the galactic centre and the \(y\)-axis is their orbital velocities. The dotted and solid lines are the predicted and actual curve that is observed.\(^a\)

\(^a\)Taken from http://en.wikipedia.org/wiki/Galaxy_rotation_problem.

on reals; this illustrates a benefit of the polymorphism in HOL over less expressive logics. Moreover, we assume both \(Thy\) and \(Sens\) contain some knowledge about shapes of curves, e.g., the curve that has a positive gradient between zero and some point and a zero gradient thereafter. A modular setup permits the extension and sharing of such ontological knowledge.

Some symbols in \(Sens\), such as \(RtV\) and \(RdV\), are not in the language of \(Thy\). To link together the seemingly disparate terms, an example axiom of the bridging meta-ontology, \(Ob\), is:

\[ \forall v, r: Real. \ (Sens \vdash \ Rad(s, g) = r \land \]
\[ Sens \vdash \ RtV(e, s, g) = v) \iff Thy \vdash \ OV(e, g, r) = v \]

which relates \(RtV\) in \(Sens\) to the \(OV\) in \(Thy\) by \(Rad\). Rubin’s proposed resolution is the hypothetical existence of dark matter, which introduces a new form of matter. In contrast, the M\(O\)dified Newtonian Dynamics (MOND) [Milgrom, 1983] argues that the definition of \(G\) is flawed and that it is not a constant, but is a function depending on the acceleration of the star. By MOND, the value of \(G\) is greater for stars with very low accelerations.

2.2 Ontology Repair Plans

We introduce here two ORPs, Where’s My Stuff and Inconstancy, and focus mostly on the diagnostic aspect, i.e. their trigger formulae.

The Where’s My Stuff Ontology Repair Plan

In physics, a common type of conflict is caused by a difference between the predicted value of some property and the value according to some corresponding sensory information arising from an experiment. This conflict is typically caused by the use of a theoretical definition that is based on an incorrect definition of the property measured or that of a dependency of the property measured. The error is generally a consequence of a misconceptualisation with a component of
the property neglected from the definition; for instance, when speaking about the matter distribution inside a galaxy, only the visible matter is included in the theoretical definition and dark matter is neglected.

Suppose an ontology $O_1$, representing the current state of a predictive theory, disagrees over the value of $f(stuff)$ with another ontology $O_2$, representing some sensory information. $f(stuff)$ might, for instance, be the graph plotting the orbital velocities of stars – a HO-object.

**Trigger:** If $f(stuff)$ has different values, the following formula will be triggered:

$$\exists O_1, O_2: Onto, \tau, \tau'\!: Types, f: \tau \mapsto \tau'; \quad stuff: \tau, v: \tau'. \quad (O_1 \vdash f(stuff) >_{\tau'} v \land O_2 \vdash f(stuff) \leq_{\tau'} v)$$

$$\quad \lor \quad (O_1 \vdash f(stuff) \geq_{\tau'} v \land O_2 \vdash f(stuff) <_{\tau'} v)$$

where $O \vdash \phi$ means that $\phi$ is a theorem of ontology $O$; $t$ $Types$ means $t$ is a type; $o:Onto$ means $o$ is an ontology; $v$ is a value of type $\tau'$; and, $>_{\tau}$ is a partial order for $\tau$.

WMS is triggered if the return value of $f(stuff)$ deduced from $O_1$ is different from that deduced from $O_2$ (9, 10). The two variables in $f(stuff)$, $stuff$ and $f$, respectively represent the part of the term that is responsible and not responsible for the conflict. WMS resolves the detected conflict by splitting $stuff$ into three parts: visible $stuff$, invisible $stuff$, and total $stuff$, and defining invisible $stuff$ in terms of total and visible $stuff$ in the repaired $O_1, \nu(O_1)$. The new $O_2, \nu(O_2)$, is the same as $O_2$ except for the renaming of old $stuff$ to visible $stuff$. If $Thy$ and $Sens \cup O_2$ in §2.1 were instantiations of $O_1$ and $O_2$, respectively, and $stuff$ was instantiated to $Glxy1$, where $\cup$ merges ontologies, then WMS emulates Rubin’s solution by introducing a third component to the galaxy: dark matter.

### 2.3 The Inconstancy Ontology Repair Plan

In order to better define a repair operation, so that, e.g., the number of possible values a new variable created by the repair process can take is dramatically reduced, extra sensory information can help resolve such ambiguity. We have identified from historical records of physics development that the inclusion of additional sensory information collected under different conditions can indeed help identify new dependencies for a property.

Suppose an ontology $O_1$, representing the current state of a physical theory, is in conflict with a set of ontologies $O_2(r_i)$, representing sensory information arising from experiments under different circumstances, represented by $r_i$, such that unexpected variations in the value of $f(stuff)$ arise under these circumstances.

**Trigger:** If $f(stuff)$ is measured to take different values in different circumstances, then the following trigger for-mulae will be matched:

$$\exists O_1, O_2: Onto, \tau, \tau'\!: Types, r_1, r_2: Glxy, f: \tau \mapsto \tau'; \quad stuff: \tau, s_1, s_2: \tau, c_1, c_2: \tau'. \quad O_1 \vdash stuff =_{\tau'} c \land O_2(r_1) \vdash f(stuff) =_{\tau'} c_1 \land ...$$

$$O_2(r_2) \vdash f(stuff) =_{\tau'} c_2 \land \exists i, j \leq n, O_1 \vdash c_i \neq_{\tau'} c_j \lor c \neq_{\tau'} c_i$$

where $O_2(r)$ is the sensory ontology containing observations made under the condition $r_i$, $Glxy$ is the type of conditions describing circumstances; $s_1$ and $s_2$ are arguments of $stuff$; and, $c_1, c_2$ are values of type $\tau'$.

Inconstancy is triggered if $f(stuff)$ is predicted to be independent of $r$, but the return values of $f(stuff)$ unexpectedly vary when $r$ varies (11, 12, 13). The resolution of the detected conflict is to retain all $O_1$-axioms in the repaired $O_1, \nu(O_1)$, and retain all $O_2(r_i)$-axioms in the repaired $O_2(r_i), \nu(O_2(r_i))$, except for the replacement of old stuff with $\nu(stuff)$ and the replacement of the definition of stuff by a new definition of $\nu(stuff)$ in $\nu(O_1)$ – the new definition establishes a relationship between $r_i$ and stuff. If $G$ in §2.1 is the instantiation of stuff, then $G$ is given a new dependency, which is the solution proposed by MOND.

### 3 The GALILEO System

Both WMS and Inconstancy have been implemented in the GALILEO system. The reasoning capabilities of GALILEO are provided by the Isabelle proof assistant [Paulson, 1994], so soundness of the reasoning is guaranteed. Beside reasoning, Isabelle provides a contextualisation facility called locales [Ballarin, 2006], which can be used for formalising modular ontologies. The GALILEO system handles flexible ontological configurations, including ontological extensions and those with heterogeneous signatures. For heterogeneous configurations, bridging ontologies are used to align signatures across different ontologies. GALILEO analyses ontologies expressed in an Isabelle theory file, in which each ontology is represented as a locale.

There are three major phases in the diagnosis procedure: a) preparation, in which the system acquires the instantiation of some of the existential variables in (9, 10) or (11, 12, 13) in order to detect a WMS type or an Inconstancy type of fault; b) conflict term search, in which all logically correct instantiations of stuff are discovered; and, c) search space control, in which only physically meaningful instantiations are retained. Below, we present our approach in more depth by applying it to an example record of ontology evolution in physics.

### 3.1 Preparation

In order to detect a WMS type of fault, the system requires an indication of the ontologies that may contain the fault, which represents the instantiations of $O_1$ and $O_2$. The system also requires a formula that expresses the conflict, $cezp$, which is a sentence that is derived to be true in one ontology but false in another. For example, in Rubin’s graph of observed orbital velocities at various radii in a galaxy $glx$, the observed velocities near the edge of $glx$ are greater than those predicted...
Inconstancy also adopts a general approach to the identification of the conflict term by matching \( \text{ceexp}_1 \) and \( \text{ceexp}_2 \) against the patterns \( f(\text{stuff}_1) \) and \( f(\text{stuff}_2) \). The system iterates through each substitution returned and generates a proof obligation for each instantiation of \( \text{stuff} \). With the substitution for Inconstancy described in §3.1, instantiations of \( \text{stuff}_1 \) could be simply \( \text{OV}(p_1, glx) \), then the proof obligation \( \exists c_1, c_2. \text{Obs}_1 \vdash \text{OV}(p_1, glx) = c_1 \land \text{Obs}_2 \vdash \text{OV}(p_2, glx) = c_2 \land \text{Thy} \vdash c_1 \neq c_2 \) will need to be discharged.

Often, the term expressed in \( \text{ceexp}_1 \) may not represent the preferred concept for repair, e.g., \( \text{ceexp} \), represents measurements on orbital velocity but the preferred concept for repair is another, such as the gravitational constant \( G \). To search for other potential concepts for repair, GALILEO automatically identifies other relevant instantiations of \( \text{stuff} \). For example, \( \text{Thy} \) contains a definition of \( \text{OV} \) in terms of \( G \) and \( M \) (2); if \( \text{stuff} \) is instantiated to \( \text{OV} \), then \( \text{stuff} \) can be instantiated to \( G \), which is the fix proposed by MOND.

### 3.3 Search Space Control

For both ORPs, the search spaces of possible substitutions are typically unmanageable because \( f \) and \( \text{stuff} \) are both polymorphic – there are more than 20,000 substitutions in both cases, but only a small fraction of these are physically meaningful. A solution is needed to avoid an explosion of substitutions.

Isabelle’s implementation of higher-order matching, like all others, returns logically correct substitutions without assessing the physical meaningfulness or relevance of the substitutions. Physical meaningfulness is crucial for controlling the search for suitable substitutions in order to perform a meaningful diagnosis, which must be compatible with real-world semantics. For instance, matcher 1 in Table 1 assigns \( \text{stuff} \) to \( \text{Glxy1} \), which is the diagnosis required. However, we argue that some other example matches have little physical content or meaningfulness, e.g., matches 6 and 7 assign \( \text{stuff} \) to a function containing the identity function and a function containing a free variable (\( ?s \)) generated by the matching algorithm, respectively.

<table>
<thead>
<tr>
<th></th>
<th>Glxy1</th>
<th>Ax.x.(Ga(Glxy1))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Glxy1</td>
<td>Ax.x.(Ga(Glxy1))</td>
</tr>
<tr>
<td>2</td>
<td>Ga</td>
<td>Ax.x.(Ga(x(Ax.x.x)))</td>
</tr>
<tr>
<td>3</td>
<td>Ga(Glxy1)</td>
<td>Ax.x.(Ga(x(Ax.x.x)))</td>
</tr>
<tr>
<td>4</td>
<td>Ax.x.(Glxy1)</td>
<td>Ax.x.(Ga(x(Ax.x.x)))</td>
</tr>
</tbody>
</table>

Table 1: Example instantiations of \( \text{stuff} \) from pattern matching \( f(\text{stuff}) \) against \( \text{Ga}(\text{Glxy1}) \).

To reduce the number of substitutions returned, several heuristics (Table 2) are designed and applied.

### 4 Evaluation

We evaluated our technique and implementation on a diverse range of records of ontology evolution in physics. Although only one example and two different fixes have been described in this paper, we base the evaluation also on examples already reported elsewhere, e.g., the bouncing-ball paradox [Chan et al., 2010] and the discovery of latent heat [Bundy et al., 2010].
Two functions of the same function symbol but with permuted argument types are the same.

Table 2: Example heuristics for pruning the solution space:
H1 ignores instantiations containing the identity function, which has no physical characteristic; H2 ignores instantiations that imply less ontological commitment than that we intended; H3 requires that the term to be repaired must contain an element of the signature, i.e. a concrete concept; and, H4 regards, e.g., $stuff : \alpha \rightarrow \beta \rightarrow \gamma$ and $stuff ; \beta \rightarrow \alpha \rightarrow \gamma$ to be the same.

2010]; the goal is to demonstrate the high level of generality of our approach, not just being able to identify various types of $stuff$, but also to handle examples across distant subfields of physics. The rest of this section covers two key areas for evaluating our work: effectiveness of search space control and meaningfulness of the generated solutions.

4.1 Reduction in Candidate Matches
Our experiment has shown that our approach to automating conflict term discovery is intractable without a reduction in the search space containing candidate matches. Even with a low unification bound, e.g., 3, the procedure fails to return a solution on all case studies. The raw search spaces are, therefore, far too vast in practice. The use of the few example heuristics in Table 2, however, prunes away from the solution scope more than 20,000 matches for the case study in §2.1 and 57,000 for both the bouncing-ball and the latent heat case studies, and enables termination. The resulting sets of matches are significantly reduced to substantially more manageable amounts of 5, 21, and 27 for each respective example. Thus, the results suggest that the heuristics used are effective in controlling the search.

4.2 Meaningfulness of Solutions
Even though the solution spaces could be considerably reduced, we will examine the degree of physical meaningfulness of the instantiations of $stuff$ in the remaining matches. For dark matter, only matches 1 to 5 in Table 1 remain in the pruned space. Every candidate match returned is in fact physically interpretable – for instance, instantiating $stuff$ to $\text{Glxy1}$ indicates that the galaxy should have an extra component; to $Ga$ leads to a redefinition of all predicted curves; and, to $Ga(\text{Glxy1})$ limits the modification to only the definition of the predicted curve for $\text{Glxy1}$.

5 Conclusion
The paper provided an overview of the GALILEO system and of two of its ORPs: WMS and Inconstancy. The diagnostic components were presented by successfully applying them to discover two fault types underlying the same set of conflicting observations in astronomy. This showed the generality of GALILEO and its ability to return only physically meaningful ontology repairs.