GALILEO: A System for Automating Ontology Evolution

Citation for published version:

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Early version, also known as pre-print

Published In:
Notes of the IJCAI-11 Workshop ARCOE-11

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
GALILEO: A System for Automating Ontology Evolution

Michael Chan   Jos Lehmann   Alan Bundy
School of Informatics, University of Edinburgh
Edinburgh, U.K.
{mchan, jlehmann, bundy}@inf.ed.ac.uk

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.
Figure 1: The x-axis is the distance of the stars in the galaxy Glxy1 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.\footnote{Taken from http://en.wikipedia.org/wiki/Galaxy_rotation_problem.}

2.1 Case Study: Predicted vs. Observed Orbital Velocity of Galaxies

Newtonian dynamics predicts that orbital velocities\footnote{We assume that observed orbital velocity and rotational velocity for stars are the same.} 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 exceed 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 \( \mapsto \) Real \( \mapsto \) 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; \( g_r \), 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; \( S_g V \), the velocity of the galactic system relative to the observer; Inc, the inclination of the galaxy; \( \lambda Shift \), the shift in wavelength; Glxy1, 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 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, \( O_b \), is:

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

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\( \text{O} \)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 stuffs 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 $Glyx1$, 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 $O_2(\vec{r}_i^*)$, representing sensory information arising from experiments under different circumstances, represented by $\vec{r}_i^*$, 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-
[Rubin et al., 1980]. Again, let Sens be the ontology containing sensory data and $Gb(glx)$ be the observed graph for glx. The diagnosis procedure begins with the substitution:

\[
\{O_1/Thy, O_2/Sens, ceexp/Ga(glx) = Gb(glx)\}
\]

since $Thy \vdash Ga(glx) = Gb(glx)$ and Sens $\vdash Ga(glx) < Gb(glx)$ as Ga and Gb are expected to be identical but Gb turns out to be greater than Ga. To ensure that the two graphs indeed disagree, the user must discharge a proof obligation in the shape of the trigger formula but with the existentials instantiated, e.g.,

\[
(Thy \rightarrow Ga(glx) \geq Gb(glx)) \land \\
Sens \rightarrow Ga(glx) < Gb(glx)) \lor \ldots
\]

in which each ontology is treated as a predicate expressed as a conjunction of its axioms. Although the system requires values of $O_1$, $O_2$ and $ceexp$ as user inputs, the instantiations of each of the remaining variables, i.e. $f$, stuff, and $v$, are automatically identified, so the rest of the procedure is completely automatic.

For Inconstancy to be triggered, pattern (11, 12, 13) needs to be instantiated. Similar to wms, GALILEO requires from the user the ontologies that may give rise to a fault – in this case, one theoretical ontology and two sensory ontologies. In addition, the system requires the terms representing the unexpected variation in each of the two input sensory ontologies, $ceexp_1$ and $ceexp_2$, respectively. For instance, suppose in two sensory ontologies $Obs_1$ and $Obs_2$, the observed orbital velocities of two stars, $p_1$ and $p_2$, unexpectedly vary. So, $Obs_1 \vdash OV(p_1, glx) = v_1$ and $Obs_2 \vdash OV(p_2, glx) = v_2$, and in the theory, $Thy \vdash OV(p_1, glx) − v_1 \neq OV(p_2, glx) − v_2$. Thus, we have the substitution:

\[
\{O_1/Thy, O_1(r_1)^/Obs_1, O_2(r_2)^/Obs_2, \\
\hspace{1cm} ceexp_1/OV(p_1, glx), ceexp_2/OV(p_2, glx)\}.
\]

Like wms, the fault is verified by discharging a proof obligation in the shape of the trigger formula, and the system then identifies various instantiations of stuff.

### 3.2 Search for Conflict Terms

Having indicated the potentially faulty ontologies and $ceexp$, GALILEO identifies instantiations of stuff to completely instantiate the relevant trigger pattern. Isabelle’s polymorphism is partial as its type unification does not specialise schematic type variables to function types. Such a constraint, which also holds in most other theorem provers, renders type unification tractable, but it is an impediment to instantiating stuff to different arity functions in different case studies. Letting stuff be a variadic function allows for high generality of the trigger. GALILEO, therefore, explicitly generates a set of types for stuff, given a maximum function order and arity.

With wms, instantiations of $f$, stuff, and $v$ can be discovered by applying Isabelle’s higher-order matching algorithm to match $ceexp$ against the pattern $f(stuff) = v$. For example, there exists the substitution $\{glx/stuff\}$ by matching with $Ga(glx)$, which suggests that the conceptualisation of the galaxy glx should be adjusted, e.g., by introducing dark matter. Unlike the HOL unification problem, HOL matching is decidable.

Inconstancy also adopts a general approach to the identification of the conflict term by matching $ceexp_1$ and $ceexp_2$ against the patterns $f(stuff_1)$ and $f(stuff_2)$. The system iterates through each substitution returned and generates a proof obligation for each instantiation of stuff. With the substitution for Inconstancy described in §3.1, instantiations of stuff, could be simply $OV(p_1, glx)$, then the proof obligation $\exists c_1, c_2$. $Obs_1 \vdash OV(p_1, glx) = c_1 \land Obs_2 \vdash OV(p_2, glx) = c_2 \land Thy \vdash c_1 \neq c_2$ will need to be discharged.

Often, the term expressed in $ceexp_1$ may not represent the preferred concept for repair, e.g., $ceexp$ 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 stuff. For example, $Thy$ contains a definition of $OV$ in terms of $G$ and $M$ (2); if stuff is instantiated to $OV$, then 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 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 stuff to 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 stuff to a function containing the identity function and a function containing a free variable (?$s$) generated by the matching algorithm, respectively.

| 1. Glxy1 | 5. \(\lambda x . x(Ga(Glxy1))\) |
| 2. Ga | 6. \(\lambda x . x(Ga(x(\lambda x . x)))\) |
| 3. Ga(Glxy1) | 7. \(\lambda x . x(Ga(x(\lambda s . s)))\) |

Table 1: Example instantiations of stuff from pattern matching $f(stuff)$ against $Ga(Glxy1)$.

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.,]
## 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.

### References


