Qualitative Causal Analysis of Empirical Knowledge for Ontology Evolution in Physics

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1 INTRODUCTION

Ontology evolution and its automation are key factors for achieving software's flexibility and adaptability. In the approach to automated ontology evolution adopted in the GALILEO[4] project, progress in physics is modelled as a process of ontology evolution. An overview of the approach is provided in Section 2. Section 3 shows that the construction and the modification of qualitative causal models of experimental set-ups make it possible to gain information about the quantities that appear in an equation and contribute to creating the logical conditions for the equation to evolve.

2 ONTOLOGY REPAIR PLANS

In the framework of the GALILEO project a number of so-called *Ontology Repair Plans* (ORPs) are being developed and implemented in higher-order logic [1]. ORPs detect and resolve a contradiction between two or more ontologies. In ORPs developed thus far, one of the ontologies represents a theory while the second ontology represents a sensory or experimental set-up for that theory. When the sensory ontology generates a theorem that contradicts a theorem of the theoretical ontology, an ORP is triggered which amends the two ontologies according to the observations. The development of ORPs is inspired by cases in the history of physics. So far, a few ORPs have been developed from a number of development cases, which reflect common strategies used in physics to cope with contradictory evidence. One of the ORPs is called *Where is my stuff?* (WMS) and was inspired by the discovery of latent heat.

Until the second half of the 18th century, the chemical/physical notion of heat was conflated with the notion of temperature and it was seen as a function of time – or of a temporal quantity, e.g. flow. Flow was defined as occurring when two physical bodies at different temperatures are in direct contact with one another. Equation 1 is a rational reconstruction[5] of this pre-modern view:

$$Q = m \times \Delta t \tag{1}$$

where Q is the heat, measured by temperature, of a physical body, m is the mass of the body, Δt is the flow of heat, measured by time, from the hotter to the cooler object.

Around 1761 Joseph Black observed that (i) ice melts at constant temperature and (ii) the time required to melt a pound of ice is 140 times greater than the time required to raise a pound of water one degree in its temperature, both the ice and the water receiving the heat equally fast. This observation required to distinguish heat from temperature, thus ultimately change the very meaning of the quantity Q. Equation 1 evolved into:

$$Q = m \times \Delta T + m \times L \tag{2}$$

where Q is the heat put into or taken out of the body, m is the mass of the body, ΔT is the change in temperature, L is the specific latent heat required by a given substance during its phase transitions.

WMS's logical infrastructure emulates part of the evolution from Equation 1 to Equation 2 and adds to Equation 1 a component for the heat transfered during phase transitions. The equation for such intermediary theory would be: $Q = m \times \Delta t + Q_{phase-transition}$. Such addition-strategy is found in other cases in physics, e.g. the postulation of dark matter or of planets to account for unpredictable yet observed gravitational behaviour in galaxies or, resp., in planetary sytems.

3 FROM THEORIES TO EXPERIMENTS

An aspect of the evolution of a physics theory that needs to be clarified is how the experimental set-up represented by the sensory ontology comes to produce evidence that contradicts the expectations of the theoretical ontology.

To this end a causal model of an experimental set-up for Equation 1 is discussed here. In particular, given the qualitative causal model shown in Figure 1, a new model is derived (Figure 2) based on principles 1 to 3 (see below). Running simulations on both models provides information (Figure 3) about the quantities that appear in the equation and create the conditions for the equation to evolve.

The causal models for Equation 1 are based on Qualitative Process Theory (QPT) [2], which allows to simulate the behaviour of a system through the explicit representation of causal relations between its quantities. The models and the results of the simulations were produced using a QTP-based tool called Garp3 (available on http://hcs.science.uva.nl/QRM/). In Garp3 terminology, a QPT model consists of a number of *model fragments* that describe their own sufficient or necessary conditions (in red resp. blue in the figures). Such fragments consist of *entity types* and *relations* between them, such as $Container$, $Substance$ and $Contains$. Entities types have *quantities*, the value of which is a combination of their positive or negative *magnitude* on a qualitative scale[6] and of a positive or neg-

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[4] Guided Analysis of Logical Inconsistencies Leads to Evolved Ontologies
[5] At the time the theory of heat was not expressed in mathematical equations.

[6] The qualitative values for $Temperature$ are named after phases. A phase $Freeze\_melt$ is included between points $Frozen$ and $Melted$ to reflect the state of knowledge at the time of Equation 1: it was believed that temperature would change during phase transitions, which requires an interval between the solid and the liquid phases.

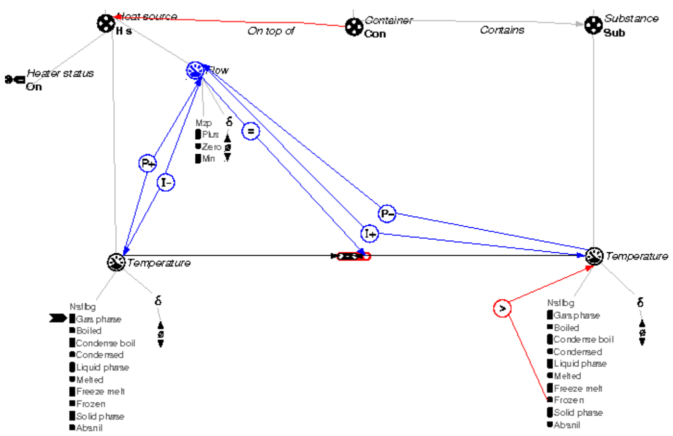

Figure 1. Process *Heat flow*: model of experimental set-up for Equation 1

ative *derivative* (δ) that indicates whether the quantity is changing in magnitude. On the other hand, complex fragments represent dynamic features as a combination of causal relations and constraints on the quantities of the entities. Causal relationships come in two flavours:

- *influences*, $I^+(Cause, Effect)$ and $I^-(Cause, Effect)$, direct resp. inverse, indicate that the effect quantity changes if the cause quantity is non zero; examples in Figure 1 are $I^+(Flow(H\_s), Temperature(Sub))$ and $I^-(Flow(H\_s), Temperature(H\_s))$.
- *proportionalities*, $P^+(Cause, Effect)$ and $P^-(Cause, Effect)$, direct resp. inverse, indicate that the effect quantity changes if the cause quantity changes; examples in Figure 1 are $P^+(Temperature(H\_s), Flow(H\_s))$ and $P^-(Temperature(Sub), Flow(H\_s))$.

A *scenario* is a description of a state containing instances of the entities described in the model fragments. In Figure 3, for instance, H_2O, for which the temperature value histories are plotted, instantiates the variable Sub of type $Substance$ of Figures 1 and 2; $Sto1$ (for stove) instantiates H_s of type $Heat\_source$. Given a QPT model of a system and a scenario, the qualitative simulation engine calculates the sequence of states that follow from the scenario, organising them in alternative sequences whenever the model contains ambiguities which allow for branching. One way of visualising a single sequence is through the value histories, as in Figure 3.

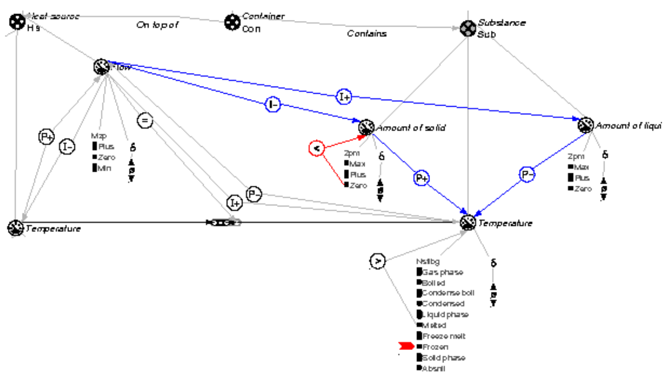

Figure 2. Process *Melting*: modified model of experimental set-up for Equation 1

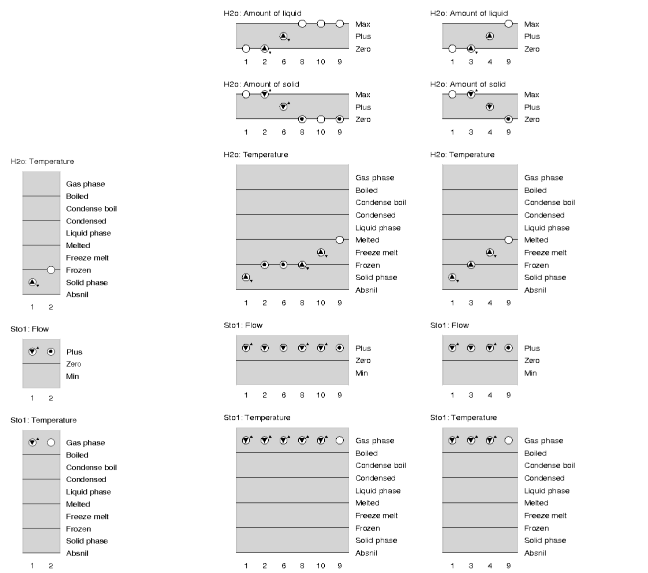

Figure 3. Left: value history for process $Heat\_flow$ consisting of 2 states. Right: two alternative value histories for process $Melting$, consisting of 6 resp. 4 states. The 6-states simulation envisions an interruption of the temperature rise, the 4-states matches the prediction of Equation 1

In order to test Equation 1 against phase changes the process $Heat\_flow$ shown in Figure 1 needs to be modified into the process $Melting$, which includes as a precondition $Heat\_flow$ (which is grayed-out Figure 2). $Melting$ is activated for $Frozen < Temperature(Sub) < Melted$ and includes quantities for phases ($Amount\_of\_solid$ and $Amount\_of\_liquid$) in order to observe Equation 1 at work during phase changes. These are phenomenological quantities, not included in the original equation, and their causal role in the modified model *should be neutral from an energetic viewpoint*, their insertion in the model should be based on the following three principles:

1. changes in their values should be direct effects of the cause quantity (i.e. $Flow$);
2. they should indirectly affect the effect quantity (i.e. $Temperature$);
3. they should exert an opposite indirect causal influence on the cause quantity with respect to the influence exerted on it by the effect quantity.

These changes to the process $Heat\_flow$ create an ambiguity in the model for the quantity $Temperature$, which during the process $Melting$ is at the same time positively directly influenced by $Flow$ and indirectly negatively proportional to it. Such ambiguity is reflected in the two alternative simulations produced by the modified model (Figure 3). The first simulation envisions an interruption of the temperature rise, whereas the second matches the prediction based on Equation 1. The very creation of the ambiguity through the modification steps 1 to 3 above sheds light on how the contradiction between the theoretical and the sensory ontology is generated.

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