Learning physical concepts using a qualitative approach: a teaching proposal

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Abstract

Nowadays the number of students that chooses science studies is decreasing, partly because the formal and abstract language that mathematics is. In this paper, our purpose is to overcome the problem and facilitate the understanding of the behaviour of physical systems without the use of mathematics as a first step.

First we have to determine the knowledge level of the people that will be taught using this new purpose. Later and, depending on that, we establish the pedagogical methodology showing the differences between the standard teaching and the qualitative one. The latter including building and inspecting general models of physical systems using HOMER and VISIGARP.

I. INTRODUCTION

Educational sciences institutions are falling in popularity due to learning difficulties that students have when they choose an education in science [1]. These difficulties could be overcome if these students are provided with a good causal understanding of the domain they are studying. In this sense Qualitative simulation based on Qualitative reasoning could be a good approach since it employs models of the domain that encode the most relevant information of the system in terms of structure, parameters and causal dependencies among them [2].

Our research topic focusses on the learning difficulties related to understanding the behaviour of physical systems. In order to establish the qualitative simulations we use GARP [1] as a qualitative simulation engine [3]. In this framework we can employ HOMER, a graphical model building environment, that allows for the constructing of models using a graphical interface [4, 5, 7]. These models, constructed with HOMER, can be used as input of GARP. To inspect the outputs, generated by GARP , we also use VISIGARP, a graphical representation tool that facilitate search, recognition and inference processes [6]. Our goal is to realise improvements in the learning processes using a learning environment based on Qualitative Reasoning and by guiding the students explorations according to their levels.

In this paper we develop a general Qualitative Model of a physical system in order to provide High School students an Assignment-Based approach [8].

[1] The software can be downloaded from www.swi.psy.uva.nl/projects/GARP/

II. THE LEARNING PROBLEM

We focus on students that have no mathematical knowledge of Ordinary Differential Equations (ODE's), that is, High School students. In order to overcome their learning difficulties we propose to improve the leaner's understanding through the ontological formalism based on the QPT framework [9]. We will tackle this task using a guided Assignment-Based approach and by defining the accompanying requirements that should be fulfilled while the qualitative model building and learning process is working [2, 5, 8, 10]:

- *Prediction and Post-diction of behaviour:* Through phenomena observation learners should be able to establish a global behaviour prediction that leads them to check if the models are working in proper way or not (behaviour analysis).
- *Deriving behaviour from the structure:* Concerns the way to encode the system studied in terms of structural parameters and causal dependencies between them.
- *Perspectives and assumptions:* Characterizing the important parameters that describe a particular perspective over the global picture under certain conditions (assumptions).
- *Causal accounts:* Causal-effect relation description.
- *Reusability:* Work out an abstract qualitative model that will be able to represent several physical phenomena.

A. Learning goals

There are two frameworks within which we can develop our learning objectives: causal and an a-causal way. The first one involves the study of “why”things work where as the second one only takes into account the “how”issue.

In physics these frameworks are represented by the kinematical and dynamical approaches for mechanical systems. Both will be used in this paper showing how a physical system works and how we have to map the information given by the empirical observations to the qualitative language.

The physical system we will study should have certain advantages: it should be simple enough for our kind of learners in order to get relevant information but not so naive that we, finally, do not achieve this goal. Furthermore our system should be general enough to represent a wide spectra of real systems in order to make it as reusable as possible.

III. THE “UNDAMPED HARMONIC OSCILLATOR”

Let us show, using an example, the usual way to teach the physical systems behaviour to the students.

Let us consider the “Undamped Harmonic Oscillator”because it is a very common physical behaviour and its mathematics, though are not very complex, are truly not trivial for our students. In order to show it, Let us considerer an spring that it’s linked with a mass as is appears in (fig 1).

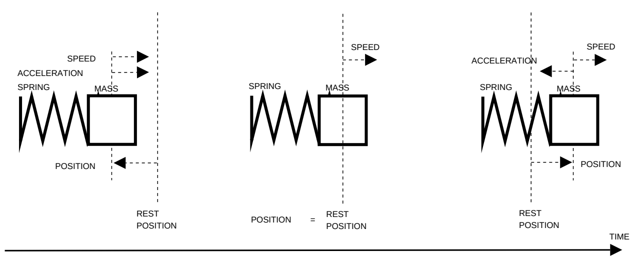


FIG. 1: Spring behaviour

First we show the relevant magnitudes that we will use to determine how the model works. The reference frameworks, with their kinematical and dynamical representation, using: kinematical relations among the spring deformation, the mass speed and the mass acceleration are showed in (fig 1). Newton’s and Hooke’s law are the interactions that, represented in a vectorial way, give sense to the movement of the mass.

A. Standard teaching approach

As we can see, in order to move the mass from an initial maximal compressed state (fig 1) the Hooke’s law gets the mass to the right being responsible for the acceleration of the mass. Using mathematical formulae this can be represented as:

$$F \equiv m \cdot a = -K \cdot x \tag{1}$$

that written in the ODE’ language and using the standard notation for the time derivative

$$\dot{x} = \frac{dx}{dt}$$

give us the Undamped Harmonic Oscillator differential equation

$$\ddot{x} + \omega^2 x = 0 \tag{2}$$

with $\omega^2 = \frac{K}{m}$.

Here we have two teaching options:

1. We can give students the solution $x(t) = A\sin(\omega t + \varphi)$ in order they prove, putting it inside (2).
2. They can solve it using the usual mathematical techniques to obtain the solution.

In both cases, we have a pedagogical problem. In the first one the students will not understand *why* the physical behavior comes from the equation (2). In the second one the students need adequate mathematical knowledge.

B. Qualitative approach

In order to build a comprehensive model for the teacher and the learner, we have to use a language very similar to the one that people use in their cognitive processes.

Let us translate the above described typical teaching procedure into QPT ontology using the HOMER and VISIGARP framework. So, we have to build a qualitative model using a new language. Our effort would not be worth while when this language is as difficult as mathematical language. We therefore have to use a language very similar to the one that people use for their cognitive processes.

The model building using HOMER starts with defining the entities that represent the physical objects relevant to the phenomenon and their subtype relationships. We also have to describe the structural relations between them and define the magnitudes that will represent, in a formal way, the relevant quantities that describe a particular perspective of the problem. A quantity space is associated to each magnitude which describes the set of values that can be assigned to the magnitude.

The qualitative parts of the models emerge through the different structural parts of the system when we relate, through functional (proportionalities) and time derivative relations (influences), the magnitudes that we have set before.

These ’model fragments’ can be used to build other qualitative models if they are general enough.

1. *The qualitative model*

At a first sight the qualitative and intuitive approach to the problem is represented by (fig 2)

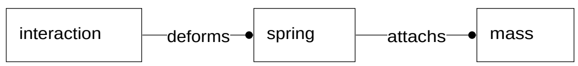


FIG. 2: Qualitative and intuitive approach

showing that there are three entities (interaction, spring and mass) connected, in such a way that the first deforms the second one that is attached to a mass constraining its movement. Once the structural relation are established, the next step consist of defining the relevant quantities that are involved in the mechanical process as is shown in (fig 3)

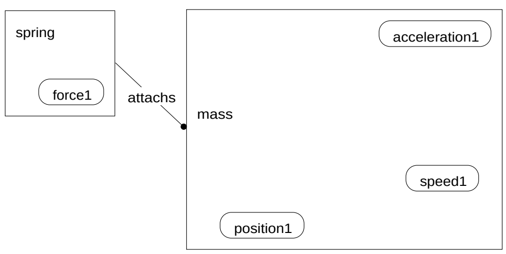


FIG. 3: Qualitative relevant quantities

Associated with the interaction entity there exists a magnitude that is the one that deforms the spring (fig 2)and that we can call external force in a very obvious way. However it does not appear in an explicit way in our model (fig 4) since it only exist in order to express the causal explanation about the spring deformation.

The mass has, as fundamental features, the position measured from the rest or equilibrium landmark (we can call it also deformation), the speed of the mass and the change of this speed with the time; that is, the acceleration. Finally, associated to the spring the fundamental characteristic is the restoration force given by Hooke's law.

Of course these quantities have several dependencies between them that provide the dynamics that characterize the system. In (figure 4) we can see that there are two positive influences between the three relevant quantities that belong to the mass entity. These influences come from the qualitative kinematical approach between position, speed and acceleration but, the proportionalities between the two entity quantities come from the causal or dynamical approach. The spring is deformed due to a force, that has a positive proportional relation with the acceleration (Newton's law) that changes the mass position in an specific way (Hooke's law) that is putting up the initial external action in a negative proportional way between this force and the spring deformation.

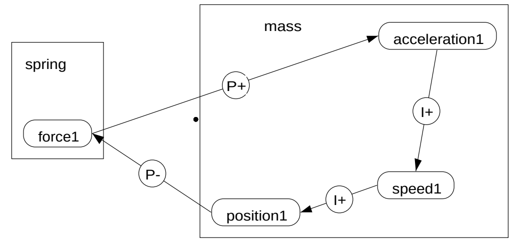


FIG. 4: Qualitative quantity dependencies

2. *Quantity spaces*

It is so important to describe properly the quantity spaces associated to the magnitudes in order to face, in a correct way, both modelling and interpretation processes. The amount of landmarks and intervals will give an idea about the information we are putting into our qualitative model. In this case we have chosen just one landmark, the rest position, that we have called zero and two open intervals (min and plus) that represent, with zero value, the whole Real number's line (the more negative the smaller quantity and viceversa). Obviously, the spring deformation has a bound and hence the speed and the acceleration. Because of the proportionality relations, also the force has a bound, so:

why haven't we introduced this obvious relation within our quantity spaces using the corresponding landmarks?

The answer to this question is not so obvious but shows how a qualitative reasoning is so powerful in order to give you the behaviour you are looking for.

The spring behaviour, that is, the oscillatory behaviour, *does not* depends on those energy constraints but just depend on the spring kinematics and dynamics. So they are not necessary if we just want to model the harmonic oscillation behaviour.

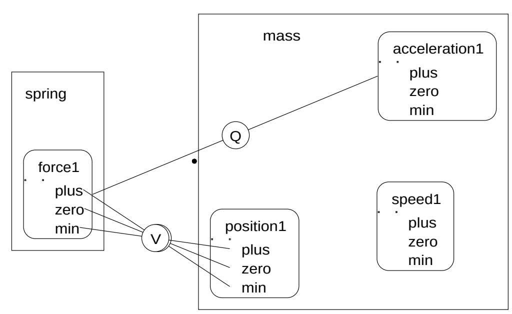


FIG. 5: Quantity spaces and their correspondences

Because the Quantity Spaces of the different magnitudes are not related to each other it is necessary to establish the suitable links among them through the correspondences (fig 5)

3. Simulation results: physical meaning

Now we are ready to generate explanations getting the results from the GARP engine using the VISIGARP interface. After running it we can see that we are the right track cause the state transition is cyclic as we can see in (fig 6)

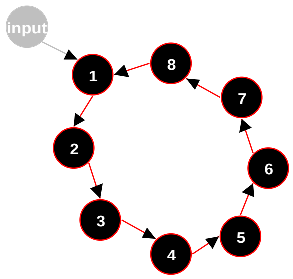
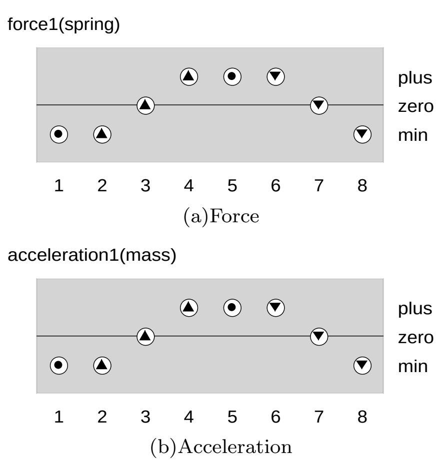


FIG. 6: State transitions

It is important to notice that the cyclic state transition already gives learners a first approximation of the oscillation behaviour because it suggests them that the phenomenon is repeated in time.

Let us see how we can obtain physical meaning from the quantity value's time evolution (history):

- In fig (7) we can see how Newton's law is working. The acceleration and force behavior are the same because both are connected by a positive proportionality.



(a)Force

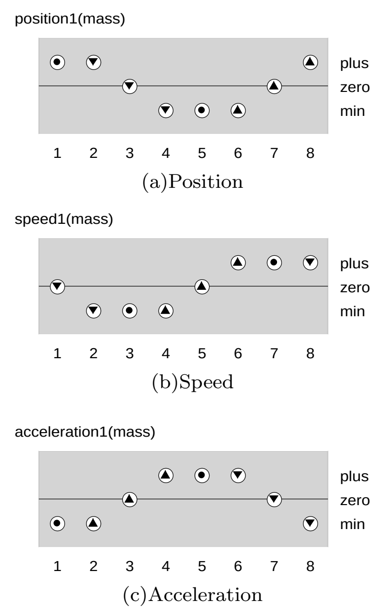
(b)Acceleration

FIG. 7: Newton's law

- From a qualitative point of view the spring behaviour is the following: Starting from an initial positive position, within plus open interval and with its trend steady (it means the spring is maximally stretched).

Because the system is symmetrical, knowing how the system works in the first four states we can easily infer what happens in state 5 to state 8. Let us see what happens in state one to state four:

1. The spring deformation and the acceleration are steady while the speed is decreasing (going to the left). Here the learners will see how the restoration force given by the Hooke's law starts to work.
2. In this state the mass is going to the rest position, so its speed is negative with the same trend than in the state before, and the acceleration is also negative and increasing.
3. Here we have reached the rest position, so the speed is the biggest one and the acceleration is zero with positive trend.
4. In this state we have already passed through the rest position. So the speed is negative and the acceleration is positive and increasing in order to decrease the speed value (restoration behaviour).



(a)Position

(b)Speed

(c)Acceleration

FIG. 8: Kinematical magnitudes

State number five will be the same as the first one but with the minus sign (spring maximally compressed), so the system shows an undamped oscillating behaviour centered in the rest position.

4. Prediction questions

As an important part of learning objectives definition and while the learner is inspecting the simulation output results, a good guiding way for oneself learning on the important concepts and relevant physical aspects is to build a coherent set of prediction questions. As an example of this point we propose the following ones:

- Which are the kinematical relevant magnitudes?

  Learners can easily identify them looking for the kinematical relevant qualitative quantities in (fig 3).

- Why does restoration force not appear under the kinematical framework?

  Because it is not a kinematical quantity but dynamical one. It is the cause of why the spring system respond to an external initial force.

- Why do the acceleration and force behave the same way?

  Because as learners can see in (fig 4) acceleration and force are related by a positive proportionality that is, if one increase the other increase, at the same time, and viceversa so, their time behaviour is the same as appears in (fig 7) (Newtons law).

- How the kinematical magnitude *position* and the dynamical *restoration force* are related and why?

  In (fig 4) one can see that position and force are related by a negative proportionality because the restoration force always is trying to bring the mass to the rest position so its sign is always the opposite to the spring deformation (position) (Hookes law).

- Why the mass speed is constant at the *rest position*

  Because, as is shown in (fig 8), when the mass is passing through the rest position (states three and seven) the acceleration is zero, so the speed remains constant and with its maximum value.

- When is the restoration force at its maximum?

  It is easy to see (fig 7(a)) that in state one, and also in state eight, the restoration force is steady. This happens because, when the spring is maximally stretched, the restoration force is in its maximum value too.

- How are the magnitude quantity spaces described and why?

  Quantity spaces are, in this case, the same for all the quantities (fig 5) and they are built in order to show the spring behaviour. So the simpler they are the more general information we get from the physical system. That is the reason because the quantity space is the following: left or minus interval (min), zero point (zero), and right or positive interval (plus).

- Which are the fundamental features of an undamped oscillation behaviour?

  The fundamental harmonic oscillation features are: the periodic behaviour, that we can see in (fig 6), and no energy constraints. This last feature is obtained by choosing open intervals instead of closed ones by landmarks that would represent the maximum values for the kinematical magnitudes that you can have for a given amount of total energy.

IV. CONCLUSIONS AND PROSPECTS

In this paper we present an example of how to improve the learning processes in a complex domain of knowledge such as the dynamical physical systems. Generating explanations through guiding interaction between learners and processes of building the model and inspecting the subsequent simulations. The articulate framework (HOMER, VISIGARP) allows teachers and learners to experiment with the different elements of the formalism which facilitates understanding in a more intuitive way, particulary concerning the meaning of abstract concepts. In our case we present the development of a general physical system, the undamped harmonic oscillator, instantiated by a mass attached by an spring. The most important features of this system are captured by the QR formalism. An important goal that is achieved is, during the building process, merging of two possible ways of facing the problem; the kinematical and dynamical approach, it means the approaches that are used to explain the systems both in not causal and causal way. In this sense Newtons and Hookes law are shown in a more intuitive way, through a graphical representation of indirect influences (positive and negative proportionalities), their deepest meaning without using mathematical expressions. The kinematical relations among position, speed and acceleration are also expressed graphically involving, through direct influences (positive influences), the changes with respect to the time. Finally we propose a set of possible prediction questions that can be used as a guidance for teachers and learners emphasizing the most important aspects of the system under study.

Summarizing, we show a new way of teaching, through an example, using QR formalism in a articulate framework going beyond learning difficulties on complex physical concepts understanding without mathematical formalism; stating hypothesis and questions that they will be able to answer by themselves discovering what happens and finding explanations for observed behaviours.

The prospect of this research could be focused on two complementary directions:

1. Checking this work with a group of High School students in order to assess our proposal.
2. We will continue developing general physical models, in order to get a repository that can be used in the future for this level of students.

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