Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Upper Secondary and Higher Education

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Abstract

This paper presents three lesson activities for upper secondary and higher education that focus on learning by constructing an interactive qualitative representation. By constructing the representation learners learn domain knowledge as well as general system thinking skills. The learning goals and the pedagogical approach are described.

1 Introduction

We investigate the pedagogical approach of learning by constructing interactive qualitative representations [Bredeweg *et al.*, 2023a]. By constructing qualitative representations, learners can develop a comprehensive understanding of subject-specific systems and improve their generic system thinking skills [Bredeweg *et al.*, 2023b; Kragten & Bredeweg, 2023].

In this paper, we describe the pedagogical approach of three lesson activities for upper secondary and higher education. The lesson activities are developed within the project Denker (https://denker.nu). The topics of the lesson activities are *photoelectric effect* (physics), *thermoregulation* (biology) and *global warming* (geography). Learners create qualitative representations using DynaLearn (https://www.dynalearn.eu). This learning space supports multiple levels at which qualitative representations can be constructed [Bredeweg *et al*., 2013]. Each successive level adds new features to describe increasingly complex system behavior. The three lesson activities presented in this paper are at level 5 of the Dynalearn software. The lesson activities were designed for learners that are already familiar with features of level 2 [grade 7-8, see Spitz *et al.*, 2021], 3 [grade 8-9, see Kragten *et al.*, 2021] and 4 [grade 10-12, see Kragten *et al.*, 2022].

Below, we first describe the vocabulary of qualitative representation at level 5 (which includes the features of level 2, 3 and 4). This paper is dedicated to providing a comprehensive and detailed description of lesson activities that involve constructing qualitative representations at level 5. For each lesson activity we describe the learning goals of the subject-specific system and explain our pedagogical approach by showing how the representation is constructed step-by-step.

2 Qualitative Representations

2.1 Vocabulary

Entities can be either physical objects or abstract concepts, while quantities represent changeable features related to those entities in a specific system. Quantities have two characteristics: a current value and a direction of change. The latter is denoted as δ. In Figure 1 there are two entities, namely E1 and E2. E1 has a single quantity, Q1, while E2 has three quantities, namely Q2, Q3, and Q4. Possible values of a quantity are described using the notion of a quantity space, which represents the characteristic states of a quantity using a range of alternating point and interval values. Q1 has a quantity space that includes the values {0, +, Point, ++}, Q2 has a quantity space with the values {0, Interval}, while Q3 has no quantity space.

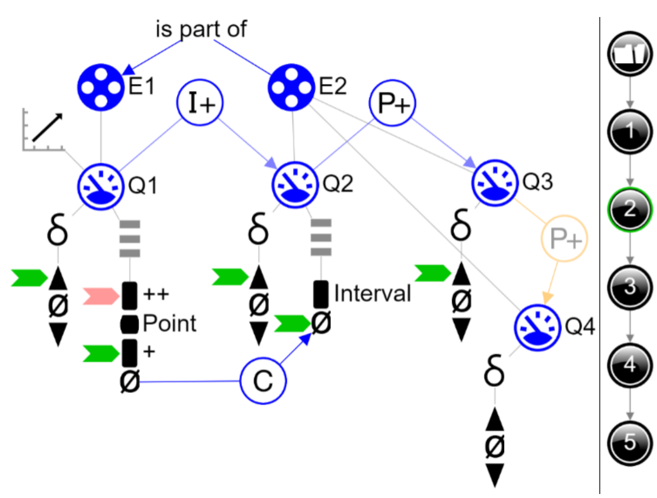

Figure 1. Qualitative representation – The simulation result of state 2 is shown.

Co-occurrence of values can be specified by adding a correspondence (C). There is a directed correspondence between values of the quantity spaces of Q1 and Q2 (if Q1 = 0 then Q2 = 0). Quantities can have causal relationships with other quantities. There are two types of causal relationships: influence (I) which is the primary cause of change, due to a process being active, and proportionality (P) which propagates change. Both relationships can be positive (I+, P+) or negative (I–, P–). In Figure 1, there is a causal relationship of the type positive influence (I+) between Q1 and Q2 (if Q1 = 0 then δQ2 = 0 and if Q1 = +, Point or ++ then δQ2 > 0). There is a positive proportional relationship (P+) between Q2 and Q3 (changes in Q2 causes changes in Q3). The notion of an exogenous influence can be used to specify a continues change for a quantity. Q1 is influenced by an exogenous influence of the type increasing. Inequalities (<, ≤, =, ≥, >) can be added to the representation to specify ordinal relations between quantities or values of a quantity space. Calculi allow qualitative calculations for operations such as multiplication or subtraction of values of quantities, resulting in the generation of a new value.

At level 5, conditional expressions can be added to the representation. Conditional expressions specify behaviors that only occur under specific conditions. Color coding is used to distinguish between the conditions and consequences of a model. In Figure 1, the positive proportional relationship (P+) between Q3 and Q4 is conditional indicated by a yellow color. The relationship is only valid if Q1 = ++ indicated by an arrow with a red color.

The qualitative representation of a system can be analyzed through a simulation that reveals the system's behavior and the direction of change of its quantities based on specified initial settings. To depict this behavior, a state graph (Figure 1, RHS) is employed, illustrating the possible states of the system. By studying the state graph, learners can gain insights into how a system evolves over time and how different factors influence its behavior. Figure 1 shows the simulation result of state 2. The representation is simulated with initial values: Q1 = 0 and an increasing exogenous influence acts on Q1. The state graph consists of five consecutive states. In state 2 Q1 = + and is increasing (δQ1 > 0), Q2 = 0 and is increasing (δQ2 > 0), and Q3 is increasing (δQ3 > 0). The change of Q4 is not determined because the condition for the positive proportional relationship to be valid (Q1 = ++) is not (yet) met.

2.2 Support

In Dynalearn, students construct representations with support based on a norm representation. This norm-based support detects differences between the student's representation and a predefined norm representation [Bredeweg *et al.*, 2023a]. An incorrect ingredient will be highlighted in red in the representation and a red question mark will appear on the right side of the canvas. A progress bar informs the students about the number of ingredients still to be added. The scenario advisor is a function that inspects the status of the model before starting a simulation and flags missing initial and/or inconsistent settings. The built-in video support functions informs students how to add ingredients to the representation (the clips are domain independent). Learners are guided using a workbook to support them with constructing the qualitative representations.

3 Photoelectric effect

The topic of this lesson activity is the photoelectric effect. It fits well into the physics curriculum of upper secondary education and higher education. Understanding the photoelectric effect in physics education is important as it provides fundamental insights into the behavior of light and electrons, serves as a cornerstone of quantum mechanics, explains experimental observations, and highlights the historical significance of scientific discoveries. The lesson was developed together with a physics teacher educator.

3.1 Subject Matter Learning Goals

The photoelectric effect is a phenomenon in physics that describes the emission of electrons from a material when it is exposed to light or other forms of electromagnetic radiation. When light interacts with a material, it transfers its energy to the electrons within the material. A key principle of the photoelectric effect is that light energy is quantized into discrete packets called photons. As the frequency of a photon increases, so does its energy. If the energy of the photons is sufficient, it can cause the electrons to be emitted from the material.

In the photoelectric effect, a crucial concept is the threshold frequency, which represents the minimum energy needed to overcome the binding forces that hold electrons within a material. This threshold frequency is unique to each specific material. When the frequency of the incident light (v) is lower than or equal to the threshold frequency (v_0) of the material, no electrons are emitted. If the frequency of the incident light (v) surpasses the threshold frequency (v_0), electrons are emitted.

The energy of a photon (E_{photon}) can be calculated by $h{\cdot}v$ where h is Planck's constant and ν is the frequency of the light. The kinetic energy (KE_{electron}) of the emitted electrons depends on the frequency of the incident light. The kinetic energy of the emitted electrons can be calculated as the energy of the photon minus the energy required to free the electron (also known as the work function Φ), so $KE_{\text{electron}} = h{\cdot}v - \Phi$. The relationship between the kinetic energy of an electron (KE_{electron}) and light frequency (v) is shown in Figure 2 (LHS).

Amplitude (A) determines the brightness or intensity of light. If the light amplitude is kept constant, the number of photons being absorbed by the material remain constant. Consequently, the rate at which electrons are emitted from the material, i.e., the electric current, remains constant as well (Figure 2, RHS).

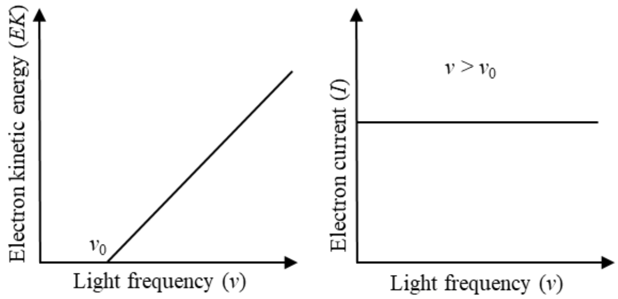

Figure 2. Photoelectric effect – Relationship between light frequency, (*i*) electron kinetic energy (LHS) and (*ii*) electron current (RHS).

Increasing the amplitude of the incident light has no effect on the energy of the incoming photon. If the frequency of the light is above the threshold and the light amplitude is increased than the kinetic energy of the electrons remains constant (Figure 3, LHS). Higher amplitude light means more photons. This results in more electrons emitted over a given time period. Hence, if the light frequency is greater than the threshold, increasing the light amplitude will cause the electron current to increase proportionally (Figure 3, RHS).

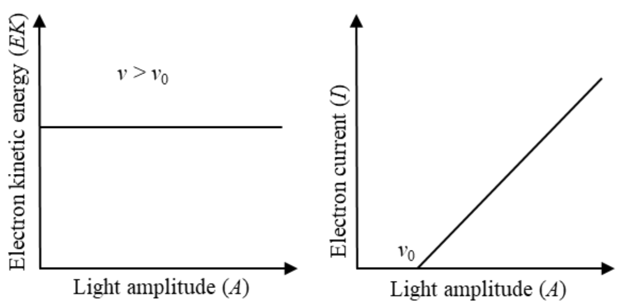

Figure 3. Photoelectric effect – Relationship between light amplitude, (*i*) electron kinetic energy (LHS) and (*ii*) electron current (RHS).

3.2 Photoelectric effect – The Representation

The final representation for this lesson activity is shown in Figure 4. The entities are *Light*, *Material* and *Electrons*. The entity *Light* has quantities *Frequency (v)* and *Amplitude (A)*, the entity *Material* has the quantity *Threshold frequency (v0)*, and the entity *Electrons* has quantities *Kinetic energy (EK)* and *Current (I)*.

3.3 Pedagogical Approach

The first part of the lesson activity focusses the relationship between the frequency of incident light and the kinetic energy of electrons.

First, learners create the entities *Light* and *Electrons*. The workbook provides an explanation regarding the nature of light, presenting it as a collection of photons that carry energy in discrete packets known as quanta. The amount of energy carried by these photons is determined by their frequency.

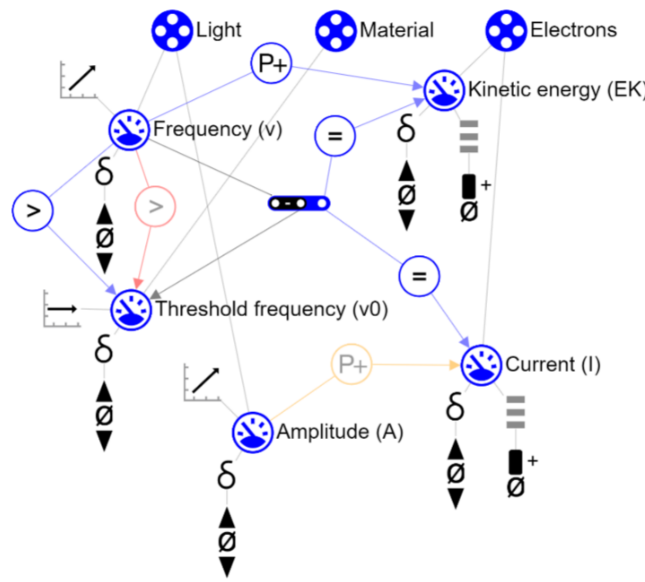

Figure 4. Photoelectric effect – Complete representation.

When light interacts with electrons, it can be absorbed by them, leading to a transfer of energy and causing the electrons to move. This movement of electrons results in the acquisition of kinetic energy by the electrons.

Learners add the quantity *Frequency (v)* to the entity *Light* and the quantity *Kinetic energy (KE)* to the entity *Electrons*. There is a positive proportional relationship (P+) between these quantities. The quantity *Kinetic energy (KE)* has a quantity space with the values {0, +}.

Learners are then instructed to set the following initial settings: an increasing exogenous influence acting on *Frequency (v)* and *Kinetic energy (KE)* is zero (0). The representation and simulation result of state 2 is shown in Figure 5.

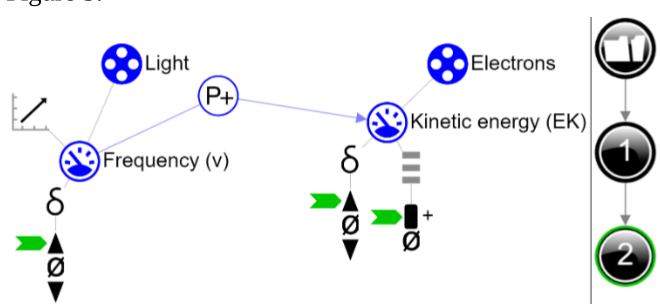

Figure 5. Photoelectric effect – Frequency of light and its effect on kinetic energy of electrons. The simulation result of state 2 is shown.

In state 2, *Frequency (v)* is increases and *Kinetic energy (KE)* is positive (+) and increasing. Learners are required to interpret the results by answering a cloze question: “In the first state the electrons *have/don’t have* kinetic energy because its value is *0/+*. The frequency of light *decreases/is constant/increases* and as a result the kinetic energy of the electrons *decreases/is constant/increases*. In state 2, electrons *have/don't have* kinetic energy because its value is *0/+*…".

Next, learners are introduced to the concept that electrons within a material possess a threshold frequency. This threshold frequency indicates that incident light must surpass a certain minimum value in order to cause the emission of electrons from the material.

Learners create the entity *Material* and add the quantity *Threshold frequency (v0)*. A calculus is created that computes *Kinetic energy (KE) = Frequency (v) –Threshold frequency (v0)*.

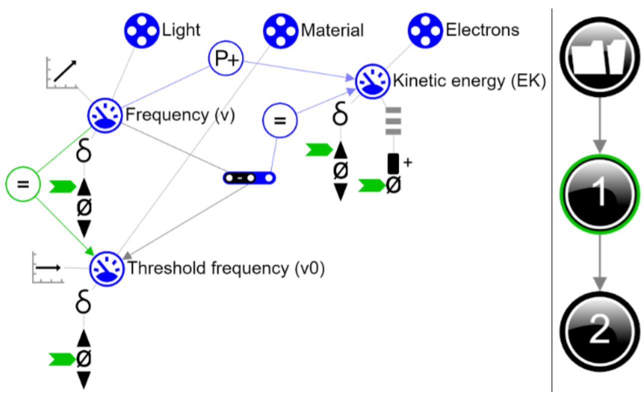

Figure 6. Photoelectric effect – Calculus of kinetic energy. The simulation result of state 1 is shown.

Figure 6 shows the representation thus far and state 1 of the simulation result with initial settings: an increasing exogenous influence acting on *Frequency (v)*, a steady exogenous influence acting on *Threshold frequency (v0)*, and an equality (=) between *Frequency (v)* and *Threshold frequency (v0)*. Note that, the value of *Kinetic energy (KE)* does not need to be specified as an initial setting because it is calculated. In state 1, *Kinetic energy (KE)* is zero because *Frequency (v0)* is equal to *Threshold frequency (v)* and increasing. *Frequency (v)* keeps increasing due to the exogenous influence. In state 2 (not shown), *Frequency (v)* > *Threshold frequency (v)* and thereby *Kinetic energy (KE)* is positive (+) and increasing.

Learners again answer a cloze questions that requires them to interpret the behavior of the system. Furthermore, learners are presented with the formula $KE_{electron} = h \cdot v - \Phi$ and Figure 2 (LHS). The qualitative representation constructed thus far encourages learners to gain insight into how this formula capture the relationships among these quantities.

In the next part of the lesson, the focus is on understanding how the amplitude of light affects the current of electrons. Learners learn that the amplitude of light only influences the current when the frequency of the light is higher than the threshold frequency. Moreover, it is explained that the amplitude of light has no impact on the kinetic energy of electrons.

First, learners add the quantity *Amplitude (A)* to the entity *Light* and the quantity *Current (I)* tot the entity *Electrons*. The quantity *Current (I)* has a quantity space with values {0, +}. Learners expand the existing calculus to include the notion that the value of *Current (I)* = value of *Frequency (v)* – value of *Threshold frequency (v0)*. So there is only a current when the frequency of the light exceeds the threshold frequency. The effect of *Amplitude (A)* on *Current (I)* is conditional. The amplitude of the light only has an effect on the current if the frequency of the incident light is greater than the threshold frequency. Learners add the conditional expression: if *Frequency (v)* > *Threshold frequency (v0)* (shown as an inequality with a red color) then there is a positive proportional relationship between *Amplitude (A)* and *Current (I)* (shown as P+ with a yellow color). Note that there is no causal relationship between *Amplitude (A)* and *Kinetic energy (KE)* and also no relationship between *Frequency (v)* and *Current (I)*.

Learners then investigate the behavior of the system under different initial settings. Figure 7 shows the representation and the simulation result with initial settings: a steady exogenous influence acting on *Frequency (v)*, a steady exogenous influence acting on *Threshold frequency (v0)*, an increasing exogenous influence acting on Amplitude (A), and an inequality relating the frequency to the threshold *Frequency (v) > Threshold frequency (v0)*.

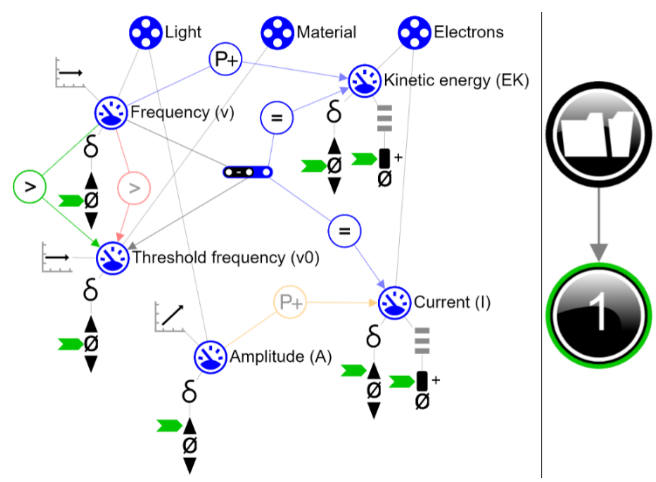

Figure 7. Photoelectric effect – Amplitude of light has an effect on the current of the electrons. State 1 of the simulation result is shown.

The simulation generates one state. The frequency of the incident light is greater than the threshold frequency so electrons are emitted and have kinetic energy (*Kinetic energy (KE)* = +). The frequency is steady so the kinetic energy of the electrons is constant (δ*Kinetic energy (KE)* = 0). There is a current (*Current (I)* = +) because the frequency of the incident light is greater than the threshold frequency. The amplitude of the light now has an effect on current. The amplitude is increasing so current is also increasing (Figure 3, RHS).

Figure 8 shows the representation of the simulation result with initial settings: a steady exogenous influence acting on *Frequency (v)*, a steady exogenous influence acting on

Threshold frequency (v0), an increasing exogenous influence acting on *Amplitude (A), and the quality Frequency (v) = Threshold frequency (v0)*. Note how increasing the amplitude has no effect on the current.

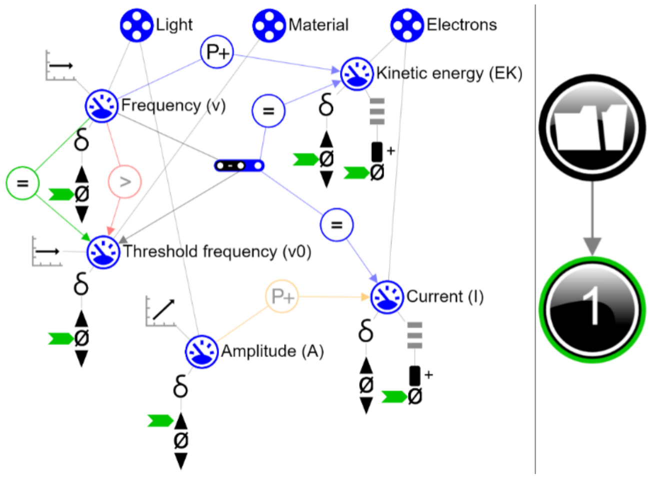

Figure 8. Photoelectric effect – Frequency of the light is below the threshold frequency therefor the amplitude of light has no effect on the current of the electrons. State 1 of the simulation result is shown.

4 Thermoregulation

This lesson activity revolves around the concept of thermoregulation. It is typically taught in upper secondary and higher education levels. Learning about thermoregulation in biology is important as it provides a foundation for understanding homeostasis, promoting human health, and exploring the diversity of life's adaptations to temperature variations.

4.1 Subject Matter Learning Goals

This lesson activity focuses on how the body responds to changes in temperature by activating heat loss or heat preservation mechanisms. Figure 9 shows a typical representation that is used in biology textbooks. When the body temperature exceeds a set point in the hypothalamus, heat loss mechanisms are activated. These include increased sweating, dilating blood vessels, and seeking shade as a behavioral response. On the other hand, if the body temperature drops below the set point, the body initiates heat preservation mechanisms. These involve constriction of skin blood vessels, stimulation of skeletal muscles to shiver, and seeking shelter as a behavioral response. Overall, this system operates as a negative feedback loop, with various mechanisms being activated above or below the set point. For instance, sweating becomes active above the set point, while shivering becomes active below the set point. However, the constriction and dilatation of blood vessels in the skin are mechanisms utilized by the body both above and below the set point.

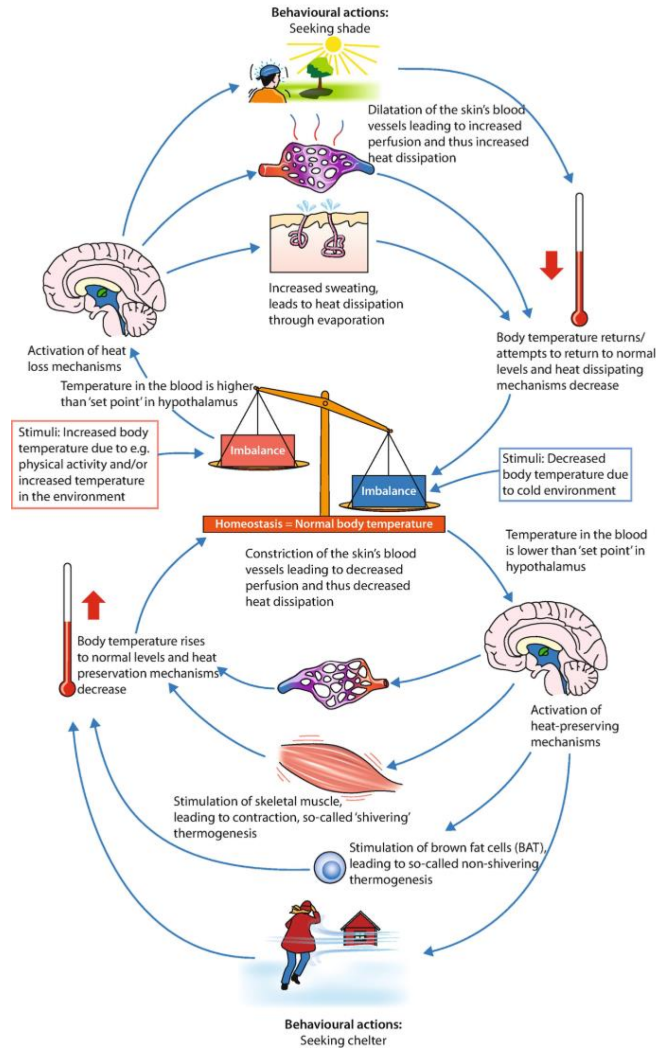

Figure 9. Thermoregulation – Image from biology textbook [Grodzinsky & Sund Levander, 2020].

4.2 Thermoregulation – The Representation

The final representation for this lesson activity is shown in Figure 10. There are five entities: *Blood*, *Hypothalamus*, *Skeletal muscles*, *Skin* and *Blood vessels*. The entity *Blood* has the quantity *Temperature*, the entity *Hypothalamus* has the quantities *Norm* and *Difference*, the entity *Skeletal muscles* has the quantity *Shivering*, the entity *Skin* has the quantity *Sweating* and the entity *Blood vessels* has the quantity *Blood flow*.

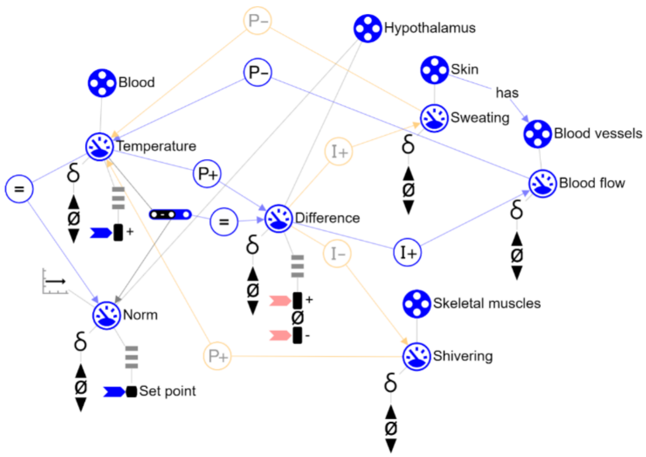

Figure 10. Thermoregulation – Complete representation.

4.3 Pedagogical approach

The first part of the lesson activity focusses on the relationship between the temperature of the blood and the hypothalamus that compares the difference with a set point.

First, learners create the entity *Blood* and add the quantity *Temperature*. They also create the entity *Hypothalamus* and add the quantity *Difference* with a quantity space with values {−, 0, +}. *Difference* is positive proportional to *Temperature.*

Figure 11 shows the representation and state 2 of the simulation result with initial settings: an increasing exogenous influence acting on *Temperature* and the starting value *Difference* = 0. In state 2, *Difference* is positive (+) and increasing (δ*Difference > 0*).

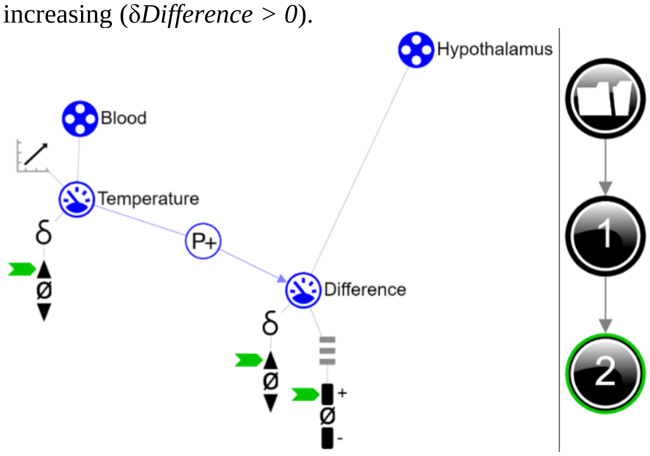

Figure 11. Thermoregulation – First simulation.

Next, the lesson activity focusses on a more precise understanding of how the difference between the temperature of the blood and the set point of the hypothalamus can be calculated.

Learners add the quantity *Norm* to the entity *Hypothalamus* and add a quantity space with point value {Set point} to it. They also add quantity space with an interval {+} to the quantity *Temperature*. Learners then create a calculus that computes *Difference* = value of *Temperature* – value of *Norm*. A constant exogenous influence indicates that *Norm* does not change.

Learners add an inequality as an initial setting between *Temperature* and *Norm* for the calculus to have an effect (without this information there is no way of knowing the outcome of the calculus).

Figure 12 shows the representation this far and the simulation result of state 1. The inequality shows that *Temperature* < *Norm* so *Difference* is negative (−). Learners are required to explain what happens by answering a cloze question: "In state 1, the temperature of the blood is *lower than/equal to/higher than* the set point of the hypothalamus so the difference is *negative/zero/positive*.".

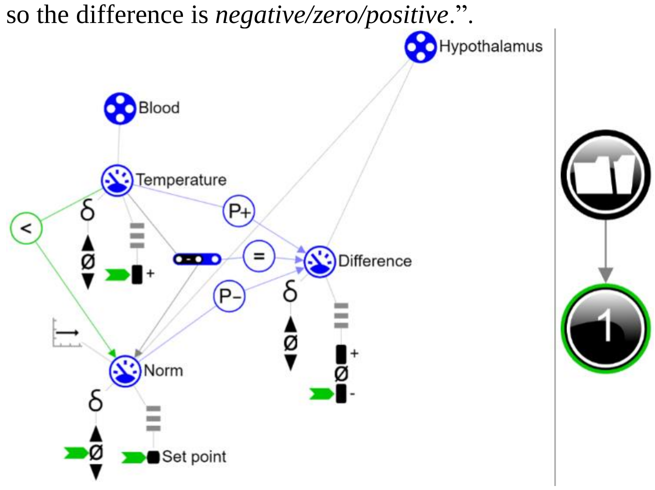

Figure 12. Thermoregulation – *Difference* is calculated by *Temperature* minus *Norm*. The inequality shows that *Temperature* is smaller than *Norm* so *Difference* is negative (−) in this state (#1).

The next part of the lesson activity focuses on the regulation of blood flow in the skin in response to deviation from the norm.

Learners are informed that the hypothalamus plays a vital role in regulating the blood flow in the skin, which directly influences the amount of heat loss by the body. Learners create the entity *Skin* and the entity *Blood vessels* and add a configuration (skin *has* blood vessel). The entity *Blood vessels* has the quantity *Blood flow*. It is explained that when the hypothalamus detects a *negative/positive* difference than the amount of impulses to the muscles that determine the diameter of the blood vessels *decreases/increases* and thereby the blood flow *decreases/increases*. Learners add a causal relationship of the type positive influence (I+) between *Difference* and *Blood flow* and a negative proportional relationship (P-) between *Blood flow* and *Temperature*.

Figure 13 shows the representation and state 1 of the simulation result with initial setting: *Temperature* < *Norm*. The state graph shows two consecutive states. In the first state *Difference* is negative (−) and increasing. The latter is due to decreasing *Blood flow* which has a positive effect on *Temperature* of *Blood*. In state 2 (not shown), *Difference* is zero (0) and *Blood flow* and *Temperature* are constant. So there is a negative feedback loop working to maintain homeostatic balance around the set point.

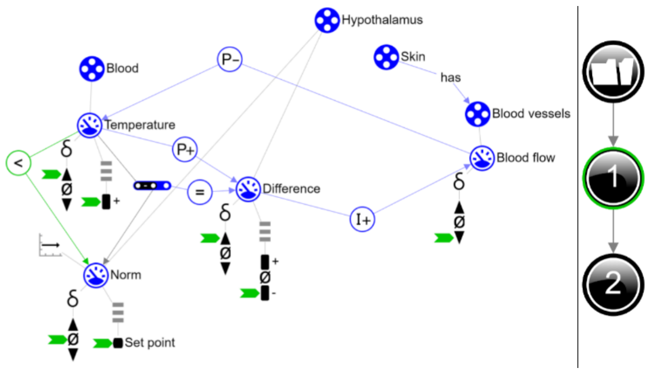

Figure 13. Thermoregulation – *Blood flow* has an effect on *Temperature* of the *Blood*.

The next part of the lesson activity emphasizes the additional measures taken by the hypothalamus in response to temperature deviations from the norm, extending beyond the regulation of blood flow.

Learners are explained that regulating blood flow is in most cases not enough to maintain a stable temperature and that additional measures are needed. Some of these measures are conditional, meaning that they are only implemented at specific temperature values. Learners first implement the shivering of the skeletal muscles as a conditional response to a negative difference between the temperature of the blood and the norm. Learners create the entity *Skeletal Muscles* and add the quantity *Shivering*. They are required to create a conditional response: if *Difference* = − then there is a causal relationship of the type negative influence (I-) between *Difference* and *Shivering* and a positive proportional relationship (P+) between *Shivering* and *Temperature*. Figure 14 shows the representation and state 1 of the simulation result with intital condition: *Temperature* < *Norm*. In state 1, *Difference* is negative (−) and increasing. The number of impulses to the skeletal muscles will increase and thereby *Shivering* will increase which has a positive effect on *Temperature*.

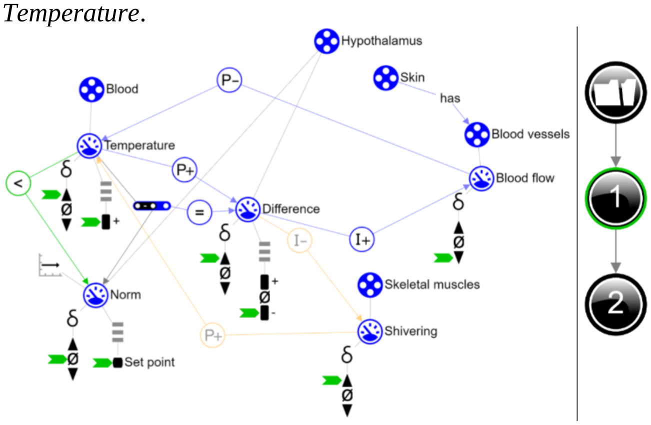

Figure 14. Thermoregulation – Shivering is a conditional response that is only applicable if the temperature of the blood is below the norm.

Learners finish the representation (Figure 15) by adding the quantity *Sweating* to the entity Skin and by adding the condition: if *Difference* = ‘+‘ then there is a causal relationship of type positive influence (I+) between *Difference* and *Sweat* and a negative proportional relationship (P-) between *Sweat* and *Temperature*.

Learners simulate the representation with initial setting: *Temperature* > *Norm*. The state graph shows two consecutive states. In the first state *Difference* is positive (+) and decreasing. The number of impulses to the skin will increase and thereby *Sweating* will increase which will increase heat loss by the skin and thereby has a negative effect on *Temperature*. Note that the other condition (*Difference* = −) is not met and that *Shivering* is not determined. Learners answer several cloze questions, e.g.: ‘If the temperature of the blood is above the norm than sweating will *decrease/be steady/increase...*’.

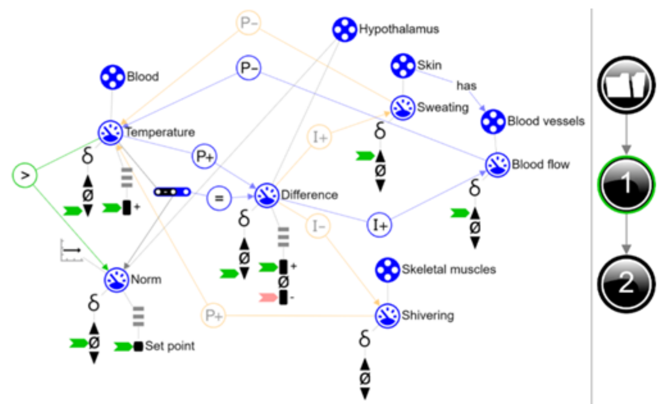

Figure 15. Thermoregulation – Sweating is a conditional response that only applies if the temperature of the blood is above the norm.

5 Global warming

The lesson centers around global warming and is well-suited for a geography class.

5.1 Subject Matter Learning Goals

This lesson has two main learning goals. First, research findings indicate that learners have a limited understanding of carbon dioxide accumulation [Qudrat-Ullah & Kayal, 2018]. The levels of carbon dioxide in the atmosphere are influenced by two primary processes: emissions by human activity (and natural processes like volcanic activity) and uptake by the biosphere, which includes processes like photosynthesis and oceanic absorption. Emissions contribute to the increase of carbon dioxide levels, while the biosphere acts as a natural regulator by taking in carbon dioxide from the atmosphere. Learners often encounter challenges in predicting carbon dioxide levels in the atmosphere based on emissions and uptake. A common misconception among learners is that a decline in carbon dioxide emissions will automatically lead to a decrease in atmospheric carbon dioxide levels. However, it is important to note that this is only true when the rate of emission is lower than the rate of uptake. The balance between emissions and uptake determines the overall impact on atmospheric carbon dioxide levels (Figure 16). This lesson aims to improve learners' comprehension in this area.

The second learning goal aims to develop learners' understanding that global warming affects different regions of the world unequally. In this lesson, we concentrate on the varying effects of temperature rise on economic production. Research findings demonstrate that as temperatures increase, there is a positive effect on economic production up to a certain threshold, beyond which the effect turns negative [Burke *et al.*, 2015].

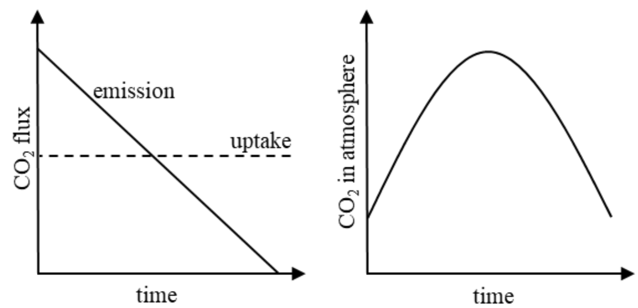

Figure 16. Carbon dioxide emissions and (*i*) uptake (LHS), and (*ii*) the impact on atmospheric carbon dioxide levels (RHS).

5.2 Global warming – The Representation

The final representation for this lesson activity is shown in Figure 17. The entity *Human activity* has quantities *Emission* and *Economic production*, the entity *Atmosphere* has quantities *CO2* and *Temperature*, the entity *Biosphere* has quantity *Uptake.*

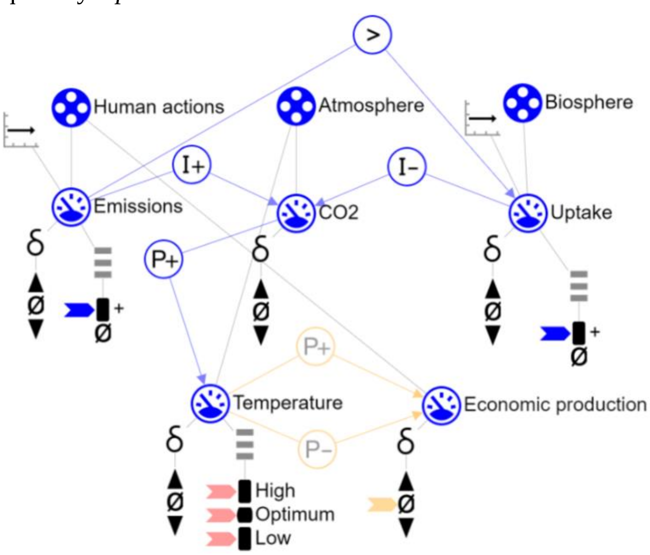

Figure 17. Global warming – Complete representation.

5.3 Pedagogical approach

The first part of the lesson activity focusses on understanding the effect of emissions and uptake on carbon dioxide levels in the atmosphere.

Learners start by creating the entity *Human actions* and add the quantity *Emissions*. Next, they create the entity *Atmosphere* and add the quantities *CO2* and *Temperature*. Learners add a causal relationship of the type positive influence (I+) between *Emissions* and *CO2* and a relationship of the type positive proportional (P+) between *CO2* and *Temperature*. *Emissions* has a quantity space with values {0, +}.

Learners simulate the representation with successively decreasing, steady and increasing exogenous influences on *Emissions*. Figure 18 shows the representation and the simulation result with the exogenous influence being steady. Given the constant emissions, learners observe that the concentration of carbon dioxide (CO2) will consistently increase. To interpret the results, learners are required to answer cloze questions, e.g., "If emission is positive and decreasing then CO2 concentration in the atmosphere *decreases/is steady/increases.*".

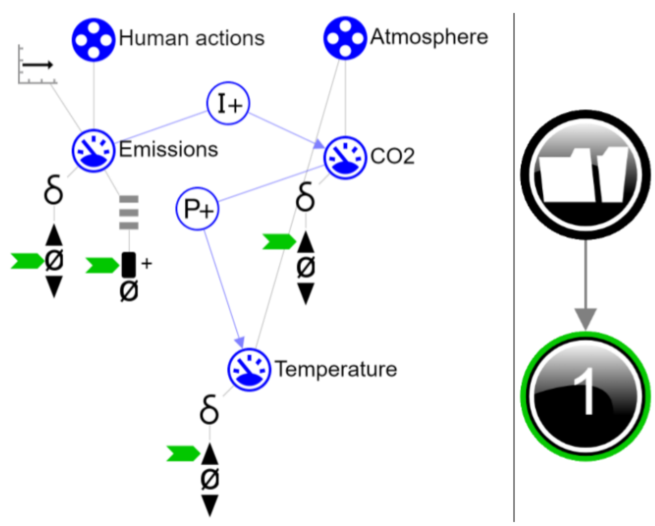

Figure 18. Global warming – The effect of emission on carbon dioxide levels and temperature.

In the next step learner create the entity *Biosphere* and add the quantity *Uptake*. The quantity has a quantity space with values {0, +} and a causal relationship of the type negative influence (I-) with *CO2*.

Figure 19 shows the simulation result with initial settings: *Emission* is decreasing, *Uptake* is steady and *Emission* > *Uptake*. The simulation result has four consecutive states.

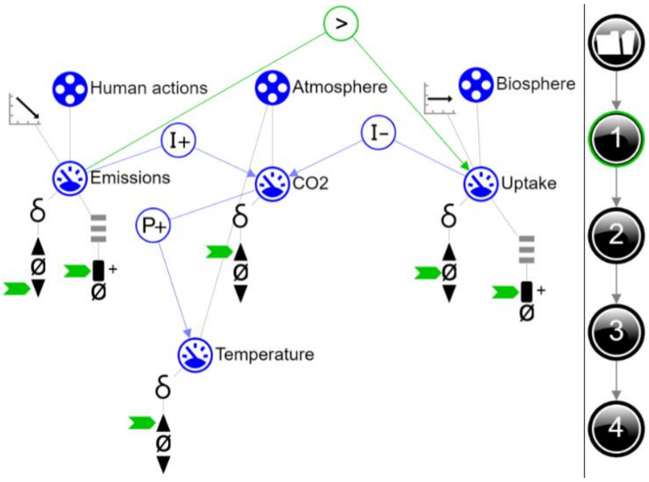

Figure 19. Global warming – The effect of emission and uptake on carbon dioxide levels.

Learners are instructed to select the four states of the simulation result and to display the value and inequality history (Figure 20). The value and inequality history displays the behavior of the system to learners in a convenient way as they do not have to click the states in the state graph one-by-one to inspect values, changes and inequalities. The value history shows that in states 1-3 *Emissions* is positive (+) and decreasing and is zero (0) in state 4 and that *Uptake* is positive (+) and steady in all states. In state 1 *Emissions* > *Uptake*, in state 2 *Emissions* = *Uptake* and in state 3 and 4 *Emissions* < *Uptake*. The value history also shows the second derivative of each quantity (if applicable). From this, learners can infer that *CO2* is decreasingly increasing in state 1. In state 2, *CO2* has reached its maximum value. In state 3, *CO2* is increasingly decreasing and in state 4 *Emission* = 0 and *CO2* is steady decreasing.

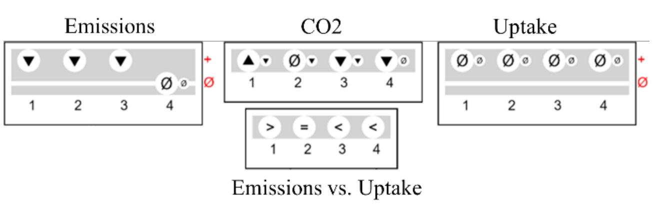

Figure 20. Global warming – Value and inequality history of the simulation result.

Learners are required to interpret the value and inequality histories and translate these into a line graph that corresponds to Figure 16. Also note that state 4 is not realistic. This provides opportunity for learners to the learn about the limitation of the representations and to think about ways to improve it.

The second part of the lesson focusses on the relationship between temperature and economic production. It is taught that the effects of global warming vary by region.

Learners add the quantity *Economic production* to the entity *Human actions* and add a quantity space with values {Low, Optimum, High}. Learners add three conditional expressions to the representation. The first expression details: if *Temperature* = Low (shown as an arrow with a red color in Figure 21) then there is a positive proportional relationship between *Temperature* and *Economic production* (shown as P+ with a yellow color). The second expression details: if *Temperature* = Optimum then *Economic production* is steady (shown as a yellow arrow on the value 0 of the derivative of *Economic production*). The third expression details: if *Temperature* = High then there is a negative proportional relationship between *Temperature* and *Economic production* (shown as P- with a yellow color).

Figure 21 shows the representation and state 3 of the simulation result with initial settings: *Emissions* is positive (+) with a steady exogenous influence acting on it, *Uptake* is positive with a steady exogenous influence acting on it, and *Emissions* > *Uptake*. *Temperature* increases in all states but in state 1 *Economic production* increases (not shown), in state 2 it is steady (not shown) and in state 3 it decreases (shown).

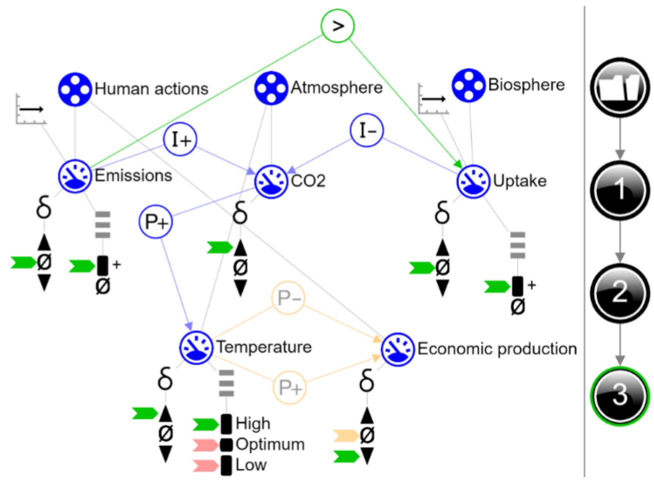

Figure 21. Global warming – The conditional effect of temperature on economic production.

7 Conclusion and Discussion

This study investigated the pedagogical approach of learning through the construction of qualitative representations. Three lesson activities were developed for upper secondary and higher education. These activities, conducted at level 5 of the DynaLearn software, aimed to enhance learners' understanding of subject-specific systems and improve their system thinking abilities. The importance and relevance of acquiring systems thinking skills are widely supported and emphasized in educational discourse [Jacobson & Wilensky, 2006; NRC, 2012]. The lesson activities focused on the *photoelectric effect* (physics), *thermoregulation* (biology), and *global warming* (geography). These topics were specifically selected because they require the use of conditional expressions, which align with the typical features of level 5 in the Dynalearn software. By focusing on these topics, we provided learners with opportunities to construct and explore qualitative representations that capture the complex and conditional nature of these systems.

With this paper we conclude a series of papers exploring the pedagogical value of interactive qualitative representations across different subjects in education. Our previous papers focused on lower secondary education (level 2 and 3; Spitz *et al.*, 2021; Kragten *et al.*, 2021) and upper secondary education (level 4; Kragten *et al.*, 2022). By incorporating qualitative representations in various subject areas, learners were able to develop a comprehensive understanding of different systems encountered in their classes. By engaging with qualitative representations, learners not only gained a deeper understanding of specific systems but also developed generic system thinking skills. This skill set is potentially transferable and can support learners in comprehending new systems by recognizing underlying principles that are often shared across domains [Goldstone & Wilensky, 2008].

The three lesson activities presented in this paper, developed as part of project Denker (https://denker.nu), exemplify the value of creating qualitative representations to enhance learning across diverse subjects. The project has successfully developed over 30 lesson activities for biology, physics, geography, and economics classes, ranging from level 2 to level 5 of the software. To facilitate easy access and immediate implementation, a collection of lesson activities ready for immediate use in the classroom can be found on the Dynalearn website (https://www.dynalearn.eu).

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