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Learning Domain Knowledge and Systems Thinking using Qualitative Representations in Secondary Education (grade 10-12)

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Abstract
This paper presents three lesson activities for upper secondary education that focus on learning subject specific knowledge and general system thinking skills by creating a qualitative representation. The learning goals and the pedagogical approach are described.

1 Introduction
The curriculum of upper secondary education contains many learning goals that require learners to understand subject-specific systems (e.g., climate, recession, gravitational acceleration, predator-prey relation). However, generic systems thinking skills are often not explicitly taught in secondary education. We investigate how qualitative representations can be used effectively as a method to develop such understanding. If learners learn the vocabulary of qualitative representations they also develop more generic systems thinking skills. Transfer of these skills might support them in understanding systems in different contexts.

In this paper, we describe the pedagogical approach of three lesson activities developed for grades 10-12. The lesson activities are developed in collaboration with educational partners (teachers, teacher educators and researchers) that participate in the project Denker (https://denker.nu). The learning goals of the lesson activities are aligned with the current curriculum of the subjects, i.e., biology, physics and economics.

Learners create qualitative representations using DynaLearn (https://www.dynalearn.nl). The DynaLearn learning space supports multiple levels at which qualitative representations can be created [Bredeweg et al., 2013]. Each successive level adds new features to describe increasingly complex system behavior. The three lessons presented in this paper are at level 4 of the DynaLearn software. The lessons were designed for learners that are already familiar with features of level 2 [grade 7-8, see Spitz et al., 2021b] and 3 [grade 8-9, see Kragten et al., 2021].

We first describe the vocabulary of qualitative representation at level 4 (which includes the features of level 2 and 3). The generic system thinking goals are aligned with ingredients of the vocabulary of level 4 (e.g., the student understands how a process propagates change to another quantity). Next, we describe the general pedagogical approach that was used during development of the lesson activities. The largest part of this paper is dedicated to giving a detailed description of the each lesson activity. 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 created step-by-step. The topics of the lesson activities are lac operon (biology), mass-spring (physics) and business cycle (economics).

2 Qualitative Representation and Generic Systems Thinking Goals
At level 2, a qualitative representation consists of entities (physical objects or abstract ideas) that can be structurally related to each other by a configuration. Entities have quantities (a measurable property) that can be connected by negative or positive causal relationships. A quantity can be assigned a direction of change (decrease, steady or increase).

At level 3, the notion of a quantity space can be added to a quantity. A quantity space consists of a range of possible point and interval values that represent distinct states of the system. A correspondence can be added to values of quantities that co-occur. An exogenous influence can be added to cause a continuous effect on a quantity and the causally related quantities for the entire simulation. The exogenous influence can make the system go through different states. An agent can be added to represent a quantity that is not part of the system.

At level 4, many new features are available and numerous types of system behaviors can be represented. The most distinct feature is that now two types of causal relationships are distinguished: proportionality and influence. When two quantities have a proportional relationships (P, P+) a direction of change in one quantity (the cause) results in a direction of change in the other quantity. Proportional relationship can be positive, both quantities change in the same direction, or negative, quantities change in the opposite direction. Note that this is the type of causal relationship that is used at level...
2 and 3 (then depicted as a +). Causal relationships of the type influence can be added to represent the relationship between a process (also represented as a quantity) and another quantity. The value of the quantity that represents the process results in a direction of change in the causally related quantity. If an influence is positive (I+), a positive value of the process results in a change in the positive direction of the influenced quantity, a negative value (a value below the point 0) results in a change in the negative direction. A positive value of a negative influence (I-) results in a change in the related quantity in the negative direction, a negative value result results in a change in the positive direction.

The availability of these two types of causal relationships allow us to represent positive and negative feedback systems. The most simple feedback system would be where a process is causally related to a quantity (e.g., I+) and this quantity directly propagates its change of direction back to the process (e.g., P-).

A simulation of the qualitative representation can be run to determine the behavior of the system (direction of change of the quantities) under the specified initial conditions. A state graph presents the possible states of the representation. Consecutive states form paths. There can be multiple paths as a simulation result and a path can be looped (the system returns to a state it has reached before). Learners can click the different states to inspect the behavior of the system. They can also select multiple states and ask for a value history that shows the value and the change of the quantity in the selected states in a graphical form. The value history can also show the change of the change (i.e., the second order derivative).

3 General pedagogical approach

Learning by creating qualitative representations is in line with learning theories such as constructivism [Papert, 1980] and constructionism [Vygotsky, 1978] as learners are actively involved in creating their own knowledge. An important aspect of this pedagogical approach is that learners are confronted with several forms of knowledge representations of systems and that they learn how to translate from one representational mode to another [Prain and Tytler, 2012]. By this they learn the constraints and affordances of qualitative representations for expressing and understanding system behavior [Disessa, 2004].

The qualitative representation of the subject specific-system is created step-by-step and features of the qualitative representation are introduced when they are relevant. Each step generally consists of i) processing new information about a part of the subject-specific system and how this can be expressed in the vocabulary of the representation, ii) extending the representation, iii) simulating, and iv) reflecting. The approach is thus aimed at understanding subject-specific knowledge and learning generic systems thinking skills in an integrated way.

There are several considerations when designing lesson activities that determine the order in which learners create the representation. Preferably, the lesson starts with learners creating a part of the representation that matches their prior knowledge. It is also convenient to let learners experience the difference between the two types of causal relationships (proportionality and influence) early in the lesson when there are only a few quantities in the representation. Furthermore, the representation must be created in such a way that at each step a simulation can be performed that provides insights into specific system behavior, e.g., consecutive states, positive and negative feedback, ambiguity.

Learners are guided using a workbook to support them with creating the qualitative representation. The workbook contains explanatory texts, diagrams, graphs, links to video’s, etc. for explaining the subject-specific system and the vocabulary of the qualitative representation. There are several exercises where learners are encouraged to think about the behavior of the system they have created thus far. Simulation results can get complicated at level 4 and learners need guidance not to get overwhelmed when many possible states and paths occur. We often use cloze questions (also known as embedded answer question) that require learners to interpret simulation results (e.g., “State 1: if process A remains constant then quantity B [decreases/is constant/increases].”). Cloze questions allow us to focus learners’ attention to relevant results and they are also efficient as it is imported to keep a good pace (teachers in the project prefer lesson activities of 2-3 hours). Note that this type of exercise is an example of how learners are required to translate knowledge from one representational mode (text) to another (qualitative representation).

There are three functions embedded in the software that support the learners: i) norm-based cueing and advice, ii) progress bar, and iii) scenario advice. The norm-based cueing and advice function detects differences between students’ representation and a predefined norm model [Spitz et al., 2021a]. An incorrect ingredient will be marked red in the representation and a red question mark will appear on the right side of the canvas. The question marked can be clicked to get more information about the incorrect ingredient (e.g., a causal relationship that is incorrect can be: of the wrong type, between the wrong quantities, have the wrong direction, etc.). The progress bar is located at the bottom of the canvas and provides information about how many ingredients of each type there are in the final representation, how many ingredients have already been created, and how many of these ingredients are correct. The scenario advice detects if all initial conditions are set for running a simulation. If not, a blue exclamation mark appears on the right side of the canvas. Learners can click it to get more information about which initial conditions need to be set.

These support functions facilitate learners to work independently and partly relieve teachers. Teachers can then focus on students that need their support for other issues.

4 Lac operon

The topic of the lesson is the regulation of the lac operon in the Escherichia coli bacterium. Transcription of the lac operon is an often used example of gene regulation in biology. It fits well into the biology curriculum of upper secondary education. The lesson was developed together with two biology teachers.
4.1 Subject Matter Learning Goals
The main goal of this lesson is to understand the regulation of the lac operon by glucose and lactose. E. coli needs glucose for cell processes. If glucose is absent and lactose is present, gene expression of the lac-operon is promoted and the enzyme β-galactosidase is synthesized. The enzyme hydrolyzes lactose into glucose. If glucose is sufficiently present, gene expression will be inhibited as a result. Glucose is dissimilated so it needs to be replenished constantly. As glucose decreases, gene expression will increase and β-galactosidase is synthesized. β-galactosidase needs to be dissimilated because enzymes are dissimilated by the cell when they deteriorate.

4.2 Lac operon – The Representation
The final representation for this lesson activity is shown in Figure 1. The entities are E.coli, Cytoplasm and Lac operon. The latter two as structurally related to E. coli, Cytoplasm has quantities Lactose, Glucose and Dissimilation (of Glucose). Lac operon has the quantities Gene expression, β-galactosidase, Lactose hydrolysis and Dissimilation (of β-galactosidase). Note that there are two quantities named Dissimilation (i.e., the decomposition of organic compounds into simpler ones) in the representation, one for the breakdown of Glucose and one for the breakdown of β-galactosidase as these are two separate processes.

The final representation is a simplification of the complete gene regulation of the lac operon, but it affords good insight into the main workings of such systems.

Figure 1. Lac operon – Complete representation. Entities are E. coli, Cytoplasm and Lac operon. There are seven quantities, such as Gene expression and Glucose.

4.3 Pedagogical Approach
The first part of the lesson activity focusses on gene expression of the lac operon for synthesis of β-galactosidase and its dissimilation. The regulation of the lac operon by lactose and glucose is addressed later in the lesson.

First, learners create the entities E. coli and Lac operon and structurally relate them with the configuration has. In the workbook it is explained that gene expression is a process and that within the vocabulary of conceptual representations the effect of a process on a quantity is called an influence (I+ and I-). Learners add the quantities Gene expression and β-galactosidase to the entity Lac operon and the add the positive causal relationship (I+) between these quantities. Learners are then instructed to set the following initial conditions: Gene expression is positive (+) and is constant and β-galactosidase is positive (+). The representation and the simulation result is shown in Figure 2. There is one state: Gene expression is positive (+) and is constant, β-galactosidase increases. Learners are required to interpret the results by answering a cloze question: “There is/is no gene expression because its value is 0/+ . Gene expression decreases/is constant/increases. As a result, the gene is expressed once/continuously and the amount of β-galactosidase decreases/is constant/increases.”.

Next, learners add Dissimilation and a negative causal relationship (I-) between this quantity and β-galactosidase. Learners are then instructed to set starting conditions for Dissimilation: positive (+) and constant. Figure 3 shows the representation and the simulation results. Learner are now confronted with an ambiguous outcome of three possible states. Students often only predict that β-galactosidase will remain constant, because the two processes cancel out. They fail to consider the fact that either process might be stronger than the others. The hypothesis is that by having learners discover this ambiguity, they will gain this understanding.

Figure 2. Lac operon – Gene expression and the synthesis β-galactosidase. The simulation result of state 1 is shown.

Figure 3. Lac operon – Effect of Gene expression and Dissimilation on β-galactosidase. The simulation result is ambiguous (state 3 is shown).
For this, learners are required to inspect the three possible states and explain what happens by answering a cloze question: “State 3, β-galactosidase decreases/is constant/increases. The production of β-galactosidase by gene expression is less than/equal to/greater than the dissimilation.”. Note that the latter sentence of the cloze question cannot be directly read off from the simulation result but has to be inferred from the increase of β-galactosidase.

The first part of the lesson is finalized with the addition of a proportional relationship between β-galactosidase and Dissimilation (Figure 4). There is now a negative feedback loop in the system. Learning about feedback mechanisms is an important aspect of biology education for many topics (e.g., hormone regulation, population dynamics). Figure 4 shows the representation and the simulation results of state 4 with the same initial conditions as the previous simulation (Figure 3). There are two end states (state 2 and 4) and three paths. The path from state 1 to end state 2 shows that a possible outcome under the initial conditions is that β-galactosidase decreases (state 1) and next (state 2) becomes constant with a positive value (+). A decrease of β-galactosidase in state 1 means that the process of Dissimilation at that moment has a greater effect than Gene expression. The decrease of β-galactosidase results in a decrease of Dissimilation and in state 2 both processes have an equal effect on β-galactosidase. In the path from state 3 to end state 2, β-galactosidase first increases (state 3) and then becomes constant (state 2). Note that, within the vocabulary of conceptual representations, the value of the value space (+) and the change (δ) of end state 2 in the path from state 1 and state 3 is the same. Learners again answer a cloze question that requires them to interpret the behavior of the system.

In state 4 (Figure 4) β-galactosidase has value zero (0) and Dissimilation is positive (+). Learners are explained that some values always co-occur in this system and that this needs to be specified in the representation by making a correspondence (IF β-galactosidase = 0 THEN Dissimilation = 0). Learners run the simulation again after adding the correspondence and discover that state 4 has been removed from the state graph as a possible outcome.

Figure 4. Lac operon – Feedback from β-galactosidase on Dissimilation. State 4 of the simulation result is shown.

The second part of the lesson is aimed at understanding how gene expression of the lac operon is regulated. By a diagram in the workbook it is explained how gene expression is promoted by lactose (lactose binds to a repressor of the lac operon) and inhibited by glucose (cAMP facilitates the binding of RNA-polymerase to the lac operon, RNA-polymerase is the enzyme that performs the transcription of genes, an increase of glucose results in a decrease of cAMP).

First, students create the entity Cytoplasm and add the quantities Lactose and Glucose. Students are then asked to add the relationships between Gene expression, Lactose and Glucose. For this, they have to reason about the type of relationship (influence or proportional) and whether the effect is negative or positive.

Next, the notion that gene expression is a result of promotion by lactose and inhibition by glucose needs to be added to the representation. As mentioned, if lactose is present and glucose is absent the lac operon will be expressed. However if glucose is sufficiently present gene expression will be completely inhibited as a result. For this, students need to create a calculus (Figure 5). The calculus states that the value of Gene expression = value of Lactose – value of Glucose. This is a difficult part of the lesson and learners are guided step-by-step through this.

Figure 5 shows the representation thus far and state 1 of the simulation results with starting conditions: Lactose is positive (+) and constant (we assume an excess of lactose), Glucose is zero (0) and constant, and β-galactosidase is zero (0). Note that, the value of Gene expression does not need to be specified as an initial condition because it is calculated. In state 1, the positive value (+) of Lactose minus the value zero (0) of Glucose results in a positive value for Gene expression. Gene expression is constant because there is no propagation of change by Lactose and Glucose (both are constant). Because Gene expression has a positive value, β-galactosidase will increase. In state 2 β-galactosidase and Dissimilation are positive and in state 3 Gene expression and Dissimilation both have an equal effect on β-galactosidase. Note that the behavior of Gene expression, β-galactosidase and Dissimilation in state 2 and 3 of this simulation are similar to state 3 and 2 of the state graph presented in Figure 4. This is an example of how the behavior of a part of the system can first be examined separately and next be incorporated in a larger simulation result.

Figure 5. Lac operon – Gene regulation by Lactose and Glucose. The simulation results in three consecutive states (state 1 is shown).
In the final part of the lesson we focus on the hydrolyzes of lactose into glucose by β-galactosidase and the feedback this induces on gene expression.

First, learners add the quantity Lactose hydrolysis and are asked to create its causal relationships. Again learners have to reason about the nature of this quantity (“Is it a process?”) and the quantities it is related to. Learners also need to add a correspondence between the value range of β-galactosidase and Lactose hydrolysis (lactose can only be hydrolyzed if β-galactosidase is present). Dissimilation (of Glucose) is not yet included. This allows us to demonstrate that glucose will completely inhibit gene expression if it is not used for cell processes.

![Figure 6. Lac operon – Glucose is produced by Lactose hydrolysis. In the end state (state 6) Gene expression is suppressed by Glucose.](image)

Figure 6 shows the representation so far and the simulation result of the end state (state 6). Gene expression is zero (0) because the positive value of Glucose (+) is now greater than the positive value of Lactose (+). β-galactosidase is no longer produced and it value has become zero (0) due to Dissimilation. Lactose hydrolysis stops (is zero) and Glucose is constant. Lactose is constant throughout the simulation (as mentioned, we assume an excess of lactose).

Finally, learners complete the representation by adding Dissimilation (of Glucose). Simulation of the model now results in 13 states: one end state (state 4) and two looped paths (Figure 7). Student are instructed to select a looped path and to display the value history of this path (Figure 8). The value 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 and changes of quantities.

Using the value history, learners can get an understanding of the behavior of this system under these initial conditions. The value history shows that Gene expression decreases if Glucose increases (state 2-6). In state 8 Glucose has reached its maximum value (change is 0 after four increasing states) and in the next state decreases because of Dissimilation. In state 13, Glucose has reached its minimum value (within the positive interval) and Gene expression its maximum value. The loop returns at state 3 where Glucose will again increase and Gene expression decrease.

![Figure 8. Lac operon – Value history of Gene expression (upper) and Glucose (lower).](image)

Learners are required to interpret the value history and to translate it into a line graph that shows how Gene expression and Glucose levels change over time.

5 Mass-spring

This lesson topic of this lesson is mass-spring system. The lesson was developed together with two physics teachers.

5.1 Subject Matter Learning Goals

The main goals of this lesson is to understand the relationship between force, acceleration, speed and extension in a mass-spring system. There are numerous misconceptions on these relationships. Those details are beyond the scope of this paper, but see [Liu and Fang, 2016; Rosenblatt and Heckler, 2011].

If it assumed that there is no friction then a mass-spring system will perform a simple harmonic motion. When a spring is pressed and then released, it will oscillate around an equilibrium position. During the oscillation, the spring is compressed and stretched. The extension (x) of the spring creates a repulsive force \( F_{\text{spring}} \) towards the equilibrium position. The repulsive force causes an acceleration (a) in the same direction. The acceleration causes a change in the speed (v) of the mass. The speed of the mass causes a change in extension. The extension creates a repulsive force, etc.
5.2 Mass-spring – The Representation

The final representation for this lesson activity is shown in Figure 9. The entity Mass-spring system has four quantities: Force (Fs), Acceleration (a), Velocity (v) and Extension (x).

![Figure 9. Mass-spring – Complete representation.](image)

5.3 Pedagogical Approach

The first part of the lesson focusses on the relationship between force and acceleration. Learners start by creating the entity Mass-spring system and add the quantities Force (Fs) and Acceleration (a). It is explained that force causes acceleration and that the relationship between these quantities is proportional. Learners then add the causal relationship (P+). As an initial condition, learners add an exogenous influence that determines the change of Force (Fs). This is needed because extension of the mass-spring system is not yet added to the representation so there is nothing that causes the force to change. Students simulate the representation with successively decreasing, steady and increasing exogenous influence. Figure 10 shows the representation and the simulation results with the exogenous influence being steady. There is no change in Force (Fs) so there is no change of Acceleration (a). To interpret the results learners are required to answer cloze questions, e.g., “If force increases then acceleration decreases/is constant/increases.”.

![Figure 10. Mass-spring – The result of the simulation with the exogenous influence being steady.](image)

Next, we focus on force having a direction (i.e., it is a vector) and that within this system we presume one-dimensional motion from the equilibrium point in the positive direction or negative direction. In the workbook we show a hanging mass-spring system and define the position above the equilibrium point as the positive direction and the position below the equilibrium point as the negative direction. This is convenient as the quantity spaces are also oriented vertically so the presentation aligns with the actual movement of the mass on the spring.

Next, learners add quantity spaces with the values negative (-), zero (0) and positive (+) to the quantities Force (Fs) and Acceleration (a). Because these values represent the direction of these quantities, change (δ) must be interpreted with regard to the present value. For instance, when the value of Force (Fs) is negative (-) and the change sign is pointing downward, the interpretation is then: force is increasing in the negative direction.

Students simulate the model with initial values: Force (Fs) is positive (+), a decreasing exogenous influence acting on Force (Fs), while Acceleration (a) is positive. Figure 11 shows the representation so far and the simulation results. The state graph consists of nine states; there is one end state (state 7) and three paths. Not all states are physically correct. Learners are asked to examine the states and to identify the correct path. Figure 11 show the simulation result of state 5. This state is not correct because force and acceleration should have the same direction. By this, learners notice that some values always need to co-occur (e.g., IF Force (Fs) = + then Acceleration (a) = +) and the need for creating a correspondence emerges. After students create the correspondence, they simulate the model again with the same initial conditions. The state graph then shows a path with the three correct states.

![Figure 11. Mass-spring – The effect of Force (Fs) on Acceleration (a).](image)

The second part of the lesson is aimed at understanding the causal relationship between acceleration and velocity. Learners are explained that the causal relationship between acceleration and velocity is not proportional but of the type influence.
Learners add the quantity Velocity (v), a quantity space with values negative (-), zero (0) and positive (+), and the causal relationship (1+). Learners then investigate the behavior of the system under different initial conditions and answer cloze questions that require them to interpret the results. Figure 12 shows the representation and the first state of the simulation results with initial conditions: Force (Fs) is negative (-), a steady exogenous influence acting on Force (Fs), Velocity (v) is positive (+). Note that the value of Velocity (v) must also be set because its initial value cannot be inferred from Force (Fs) or Acceleration (a). The simulation results in three consecutive states. In the first state Acceleration (a) is negative and constant. Velocity in the positive direction is decreasing. In other words, the mass is still moving in the positive direction but is slowing down. In the second state Velocity (v) is zero (0). In the end state (state 3) Velocity (v) is in the negative direction and increasing (as mentioned, the arrow of the change sign is then downwards). State 3 demonstrates that the velocity of an object will increase as long as there is a net force in the same direction.

The last part of the lesson activity focusses on the relationship between velocity, extension, and on the repulsive force of the spring towards the equilibrium position when it gets extended. Learners add the quantity Extension (x), a value space with values negative (-), zero (0) and positive (+), and the causal relationship (1+). Note that the relationship between Velocity (v) and Extension (x) is also of the type influence. As mentioned, force and extension are always in the opposite direction. For this, learners add an inverted correspondence (C with U-turn arrow) between the value space of Extension (x) and Force (Fs). They also add the negative proportional relationship (P-) between Extension (x) and Force (Fs).

The complete representation (Figure 9) is then simulated with the initial condition: Force (Fs) is positive (+) and Velocity (v) is zero (0). The initial value of Extension (x) does not need to be set because it is fixed by the value of Force (Fs). The simulation results in a looped path of eight consecutive states. Learners are instructed to select the path and to display the value history (Figure 13). The value histories of Acceleration (a), Velocity (v), and Extension (x) now show that the values and changes of these quantities along the states can be characterized as three sinus waves that are out of phase. In the first state, Acceleration (a) is in its maximal positive direction, Extension (x) in its maximal negative direction and Velocity (v) is zero. In a hanging mass-spring system this represents that the mass is in its most downward position, that the spring is maximally stretched so acceleration is also maximal and that at this position the velocity is zero. In state 2, Acceleration (a) decreasingly decreases (arrows of change and change of change both are down) in the positive direction. Velocity (v) increasingly increases in the positive direction, because the direction (the value) of Acceleration (a) is positive (and thus in the same direction as velocity). Extension (x) is negative and is increasingly increasing in the positive direction.

In the third state Extension (x) is zero. The mass is now in the equilibrium position. At this point there is no force acting on the mass so Acceleration (a) is zero. Velocity (v) is at its maximum in the positive direction. In the fourth state the mass passes the equilibrium point and the repulsive force and thereby the acceleration are now in the opposite direction of the velocity. So, Velocity (v) is (still) positive but the mass is decelerating because Acceleration (a) is negative. In the fifth state, the mass is in its most upward position and the spring is maximally compressed. In states 6 to 8, the mass moves to its most downward position, which is again reached in state 1.

In the final exercise, learners are requested to examine the value histories and to represent each of them in a line-graph.

### 6 Business cycle

The lesson topic of this lesson is the business cycle. The lesson was developed together with an economics teacher.

#### 6.1 Subject Matter Learning Goals

This lesson activity focusses on how alternating periods of expansion and contraction of the economy can be influenced by governmental policy. These fluctuations in output of the
economy are often referred to as the business cycle. Real gross domestic product (real GDP) is the most used macroeconomic measure of the value of economic output. Potential GDP is an estimate of what an economy could feasibly produce when it fully employs its available economic resources. The difference between the level of real GDP and potential GDP is known as the output gap. When real GDP is less than potential GDP, the output gap is the economy is experiencing a period of recession which causes unemployment to increase. When real GDP is higher than potential GDP, the output gap is positive. The economy is then performing above potential and jobs become available. Government can follow a counter-cyclical policy in an attempt to influence the output gap. When the output gap is negative, the government can take measures to decelerate the economy. When the output gap is positive the government can decelerate the economy.

6.2 Business cycle – The Representation

The final representation for this lesson activity is shown in Figure 14. The entity Economy has four quantities: Potential GDP, Real GDP, Output gap and Unemployment. The external agent Government has the quantity Measures.

6.3 Pedagogical approach

The first part of the lesson activity focusses on the relationship between the real GDP, the potential GDP and the output gap.

First, learners create the entity Economy and add the quantities Real GDP, Potential GDP and Output gap. It is explained that Real GDP has a positive proportional relationship with Output gap. Potential GDP has a negative proportional relationship with Output gap. Learners then add the causal relationships. Figure 15 shows the representation and the first state of the simulation results with initial conditions: a steady exogenous influence acting on Potential GDP (change of this quantity is fixed during the simulation). Output gap is increasing.

Next, the lesson activity focusses on a more precise understanding of output gap. As mentioned, output gap is positive when real GDP is larger than potential GDP and negative when real GDP is smaller than potential GDP. For this, students create a value range for Output gap with values negative, zero and positive and a calculus. The calculus states that the value of Output gap = value of real GDP – value of Potential GDP. An exogenous influence that acts on the change of Real GDP needs to be added as an initial conditions for Output gap to reach different states (-, 0, +). Learners also need to add an inequality as an initial condition between Real GDP and Potential GDP for the calculus to have an effect (without this information there is no way of knowing the outcome of the calculus). Note that in this part of the lesson activity many ingredients need to be added before a meaningful simulation can be performed. Figure 16 shows the representation this far and the simulation result of state 1. The state graph shows that there are three consecutive states. The inequality shows that Real GDP is smaller (<) than Potential GDP so Output gap is negative (-) in this state (state 1). In state 2, Real GDP equals (=) Potential GDP and Output gap is zero (0). In state 3, Real GDP larger (>) than Potential GDP and Output gap is positive (+). Output gap keeps increasing because of the increasing exogenous influence that acts on Real GDP. As is often the case in the workbook, learners are required to explain what happens by answering a cloze question: “State 1. Real GDP is smaller/equal to/larger than Potential GDP so the output gap is negative/zero/positive.”.
The last part of the lesson activity focuses the use of a counter-cyclical policy by the government and how this has an effect on the system. Learners are explained that governments can apply stimulating and decelerating measures to steer the economy in the desired direction. Learners create the agent Government and add a quantity Measures with a value range with values Decelerating, zero (0), and Stimulating. They are explained that these measures can be seen as a process, i.e., if the measures (e.g., investments) are implemented, they will continue to exert their effect on the output of the economy. Learners add a causal relationship (I+) between Measures and Real GDP. Figure 17 shows the representation and state 1 of the simulation results with starting conditions: Measures is Stimulating and Real GDP is smaller than Potential GDP. The state graph shows three consecutive states that are identical to previous simulation results.

Next, learners finish the representation by adding the quantity Unemployment and the causal relationship (I-) between Output gap and Unemployment. It is explained that the government might decide to take measures based on increasing or decreasing unemployment numbers. Learners add a positive causal relationship (P+) and start a simulation with the same initial conditions as the previous simulation. Simulation of the model now results in eight consecutive looped states.
suited to start developing system thinking skills in lower secondary education [Spitz et al., 2021; Kragten et al., 2021]. Level 4, the focus of the present paper, better aligns with topics and cognitive development of learners in upper secondary education. For instance, the distinction between two types of causal relationships (proportionality and influence) is difficult for learners but present in many topics throughout the curriculum of upper secondary education. For all levels it is likely that a single lesson activity is not enough for learners to get a full grasp on the concepts. In the project Denker, participating schools conduct three lesson activities on the same level per year.

Finally, there are many topics in secondary education where learning by creating qualitative representations can be of value. This paper presents three examples of lesson activities that demonstrate the potential of this approach. We hope that these examples enthuse educators and other stakeholders and that learning by creating qualitative representations finds its way into many classrooms.

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