Learning to Connect the Macroscopic and Microscopic Variables of the Ideal Gas Law by Using Drawing-Based Modeling

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Abstract

The difference between macroscopic and microscopic scales are difficult for students to understand. The ideal gas is a representative topic in high school physics and chemistry that requires students to connect micro-level and macro-level of gas properties. In order to solve the problems which students have for connecting microscopic and macroscopic variables of the ideal gas law, in this research, we used drawing-based modeling, known as SimSketch, to visualize the micro-level movement of the ideal gases and to guide students to learn one part of the ideal gas law. We have developed and adjusted SimSketch for two iterations. In each iteration, the dialogue and the written answers of five dyads of students were analyzed. We found five themes of how students connected the microscopic variables to the macroscopic variables. Through further analysis, these themes might stem from the representations and tasks demonstrated in SimSketch. Our findings suggest that drawing-based modeling can guide students to connect the micro-level and macro-level gas properties along with guiding tasks but the choice of the representations in SimSketch may affect students' interpretation of the micro-level properties of ideal gases. With inexplicit representations, students may have an incomplete knowledge regarding the connection of microscopic variables and macroscopic variables but may provide more in-depth conversations.

Keywords: drawing-based modeling, macroscopic variables, microscopic variables.

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Macroscopic scale and microscopic scale are two essential ideas in science education. Macroscopic scale refers to things we can touch and sense, whereas microscopic scale refers to things such as molecules and atoms. The ability to explain the microscopic dynamics is necessary for students to comprehend the macroscopic consequences. Researchers found out that students often ignore microscopic behaviors while explaining macroscopic phenomena (Li & Black, 2016; Lucas, 2014). Due to the difficulties in bridging these two different levels in science (Li & Black, 2016), it is reasonable to emphasize the connection-making across different levels in physics and chemistry in an early stage (Chabay & Sherwood, 1999). A representative topic that requires students to understand microscopic behaviors and to connect them with macroscopic consequences in the secondary education is the ideal gas law (Bowen-Jones & Homer, 2014; Morris, 2015).

As students have difficulties to understand microscopic and macroscopic connections in general, students also have difficulties in interpreting both macro-level and micro-level perspectives of the ideal gas law (Lin & Cheng, 2000; Li & Black, 2016; Liang et al., 2011). In the ideal gas law, students do not only have to understand the dynamic behavior of gas particles, but also need to connect microscopic dynamics to the macroscopic gas properties (Li & Black, 2016; Loverude et al., 2002), such as connecting pressure to collisions and connecting temperature to the speed of particles in a container. In terms of macroscopic variables, students tend to link pressure with volume, or link pressure with temperature intuitively and ignore that these laws require that other variables such as the number of particles need to be constant (Kautz, 2005a; Medden et al., 2011). As for microscopic manifestation, novice learners usually view molecular representations differently than experts (Madden et al., 2011). Even university students may mistakenly assume that more collisions produce higher temperature (Kautz, 2005b). These incorrect or incomplete understandings of the microscopic model of particles will largely influence students' conceptual understanding of the ideal gas law and prevent them to reason about certain physics phenomenon (Kautz, 2005b; Eylon & Uri, 1990).

Traditional lessons of ideal gas law include using graphs and equations (Kautz et al. 2005b). However, these abstract graphs and equations represent macro-level gas behaviors make learning even more difficult (Li & Black, 2016). Researchers (Madden, 2011; Kozma & Russell, 2005) recommended to utilize multiple representations, including computer modeling, interactive visualization, graphs, and sketches for physics for chemistry learning. Specifically, visualization software or simulation-based environments are effective tools that can illustrate macro- and micro-levels of a scientific topic (Madden et al., 2011; Li & Black, 2016; Russell et al. 2000).

Computer modeling and simulations have advantages of making invisible visible and operating input to observe output (Schmalz, 2012; De Jong & Van Joolingen, 1999). The things we cannot see in the real-life situation can be easily demonstrated through simulations. In the history, scientists have used simulation to calculate and develop complex systems. By interacting with and manipulating computer simulation, students may experience similarly as experiments performed by scientists (Wieman et al., 2008). Moreover, research shows that the use of simulations has positive influences on students' learning (McKagan et al., 2008; Wouters, 2017)

In 1999, Chabay and Sherwood stated that simulations were beneficial for students to connect multiple levels and concluded that computer modeling can largely enhance the microscopic model of thermal properties of matter. In 2002, Fratz and his colleagues investigated four pairs of students using modeling software. They illustrated that students developed various modeling practices while manipulating the software scaffolds. Later in 2004, Hansen and his colleagues confirmed that students with experience in three dimensional computational models tended to have a more scientifically sophisticated understanding. Although research indicates that computer simulations are powerful tools (Louca & Zacharia 2012; Chabay & Sherwood,1999), the effect of using simulations depends on many factors, such as simulation environments, multiple representations and scaffolding (De Jong & Van Joolingen, 1999; Anisworth, 2006; Li & Black, 2016), wherein simulation environments is a fundamental of engaging students in learning and providing support during the learning process. Consequently, a simulation such as drawing-based modeling with an interactive environment and multiple perspectives will be promising for our research.

Drawing-based Modeling

Unlike many modeling tools in which students need to learn syntax and semantics, drawing-based modeling does not require students to have any computer knowledge. It specifically refers to as the simulations supported by free-hand drawings (van Joolingen et al., 2014), which is also known as SimSketch. We used SimSketch as a simulation tool to guide students to learn the ideal gas law. In SimSketch, students are allowed to give their sketches. By adding behaviors to their draft, their sketches can move and demonstrate the dynamic behavior of particles (Schmalz, 2012; Van Joolingen, 2016).

Compare to other simulations which are closer to the real-life demonstration, SimSketch is similar to students' dynamic sketches. It illustrates abstract models instead of amplification of life scenes. In science education, it is hard to imagine learning science without the use of visual representation (Quillin & Thomas, 2017). In physics, the drawing of abstract visual models is often used as a tool for understanding and analyzing problems. As Quilin and Thomas (2017) mentioned in their research, drawing in science is a learner-generated external visual representation which consists of structure, relationship or processes. Hence, through the use of sketches, students are able to identify the relevant variables in the system (van Joolingen et al., 2014).

Besides sketches, drawing-based modeling requires students to label model elements to their drawings. Adding behaviors to the sketches is a method of an unfolding story. Instead of a chain of deduction, students encounter two distinct stages: first, the situation when there are no properties, such as gravity or speed; Second, introducing the concept of gravity or speed (Besson, 2001). With sketches and the structure of behavior building, SimSketch bridges the gap between informal, sketch-based representations and formal, executable models (van Joolingen et al., 2012).

Apart from using SimSketch to represent abstract models, a sufficient level of scaffolding is necessary to guide student learn the ideal gas law as well (Heijnes et al., 2017). In our research, we adopt SimSketch as a tool, supporting model-based learning to engage students to learn and reason about the ideal gas law models.

Model-based Learning

In Model-based learning, students need to create their own models (McKagan et al., 2008). Scientific models routinely serve as representation of abstract concepts for scientific theories (Treagust et al., 2002). Developing students' ability of constructing models is helpful for students to make sense of abstract and difficult science concepts (Grosslight et al., 1991; Treagust et al., 2002). Although there are no strict processes of how model-based learning works, many studies agree that there are four typical steps. These four steps are collecting information, constructing basic models, evaluating the models and revising models (Louca & Zacharia, 2012). Students can develop relation-based thinking (a way of decomposing a system into smaller, easily identifiable parts and exploring the causal relations of these parts) and model-based thinking (a way of developing mechanism form recreating the parts of a system) by following model-based learning (Fretz et al., 2002). The relation-based thinking and model-based thinking are two aspects of a physical system (Miller et al., 1993), which facilitate students to shift from remembering non-caul representation to a causal model. Therefore, we designed the guiding tasks in SimSketch based on the Model-based learning processes.

Research Question

We chose the ideal gas law as a typical example for learning the connection between macroscopic and microscopic view and developed a new configuration of SimSketch to guide students to learn the ideal gas law. We assume by using SimSketch, students who have not learned thermodynamics are able to connect microscopic and macroscopic variables of the ideal gases. In the end, we expect to improve learning environments or functions in the drawing-based modeling, as well as bring out more profound insight about how the representations in SimSketch support or deter students' understanding.

Based on the interests above, the research question is formulated as:

How do students learn to connect the microscopic and macroscopic variables of the ideal gas law using drawing-based modeling?

In order to answer this question, these two questions needed to be answered first:

Whether do students connect microscopic and macroscopic variables of the ideal gases using drawing-based modeling?

How do students connect macroscopic and microscopic variables while learning the ideal gas law?

Method

This study adopts the drawing-based modeling tool, also known as SimSketch, to build a simulation in which students can create their gas models and explore the movement of the gases. There are seven tasks on SimSketch that guide students to learn about the behavior of the gases step by step. In order to check students' previous knowledge and understanding of the ideal gases, one pretest and one posttest were given to students. We have run the study for two iterations. In each iteration, students' conversation and interaction with SimSketch were recorded and coded. Additionally, the hypothesis learning trajectory is used for analysis. Based on the limitations of the first iteration, some changes were made in the second iteration.

Participants

Participants were in the fifth year of Middle Year Program (MYP5) from 3 international schools. All of these international schools follow the International Baccalaureate (IB) curriculum. The participants were voluntarily assigned to our research through emails. They all took physics lessons in MYP 5 and were interested in science. In total, 30 students participated in this research. Because of the quality of recording and arrangement problems, 10 students were discarded from analysis. Consequently, in the first iteration, 10 students (5 dyads) were included for analysis, followed by another 10 students (5 dyads) in the second iteration.

In principle, grade 10 (MYP5) students should have some knowledge about force, temperature, volume, states of matter, atoms and molecules, but about pressure and accurate definition of pressure and temperature (Morris, 2015). This has been proved by students' pretest (see Appendix). During the research, students worked in pairs on one laptop, which belongs to researchers. SimSketch was stored on the laptop of the researcher and could not be found elsewhere. The participants did not have access to SimSketch before or after the research.

The Materials and Tasks

The tasks and reading materials are based on the IB curriculum textbook (Morris, 2015) and the University Modern Physics (Young & Freedman, 2012). Because our study focuses on the connection between the macro-level and micro-level connection of the ideal gases, the pressure and temperature cannot be directly changed. They are shown on the graphs as a macro-level representation. Therefore, we selected the relationship between volume and pressure (Boyle's law), temperature and pressure (Gay-Lussac's law) as reading materials since they were easier to operate in SimSketch. The relationship between volume and the number of moles will not be considered due to the representations in SimSketch.

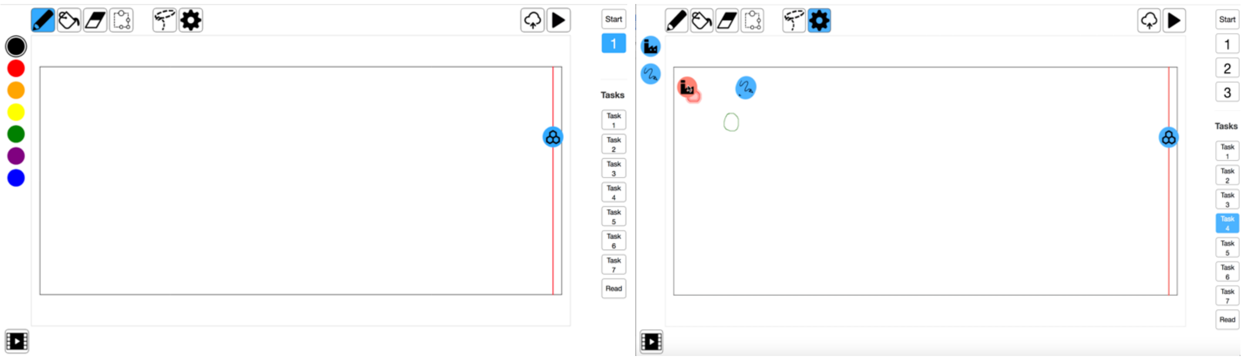
We designed a pre-test, a post-test and seven tasks (see Appendix) for students to learn the ideal gas law, based on the process of model-based learning. The pre- and post-test contains two questions respectively. In the pre-test, students are required to draw their particle models and write down what they know about pressure and temperature. In the post-test, students need transfer their knowledge to draw particles models for a weather balloon and to solve one problem about the weather balloon. The seven tasks include three written tasks and four verbal tasks. In the first iteration, task 1 and task 2 guide students to explore the relationships between speed and temperature, and the pressure of the ideal gases. Task 2 intended to construct a basic model for students about pressure. Task 3 were designed for constructing a more complex model of volume and pressure. We expected students to follow the questions in task 3 and evaluate their hypothesis. After manipulating on SimSketch, students should revise their hypothesis. In task 4, students were asked to apply their revised model to predict a new model for the number of particles of the ideal gas law. Students were expected to follow the same process as task 3 and modify their model again. When they finished the first four tasks, Boyle's law and Gay-Lussac's law were presented in task

5. Students were asked to explain these two laws and to connect these two laws with what they did and saw in previous tasks. Task 6 and 7 were meant for researchers to know the limitation of SimSketch and how students perceived the microscopic scale of the ideal gases from SimSketch representation. From task 4 to 7, students did not have to type answers on the computer. Instead, researchers would interact with students and try to stimulate their deep understanding of the ideal gases.

In the second iteration, we replaced the original question to a more explicit one in task 1, asking students to explain the reason behind their answers. In task 3, we added a table in order to provide a new aspect for students to reject their false or incomplete hypothesis. We expected this table would encourage students to remember controlling variables and to generate a more complex understanding of the ideal gas law. We changed task 4 to focus on the relationship between temperature and pressure in order to aid students to understand Boyle's law and Gay-Lusacc's law in task 5. Maybe they would think more deeply in task 5 because of the change. Other tasks remained as the same in the first iteration.

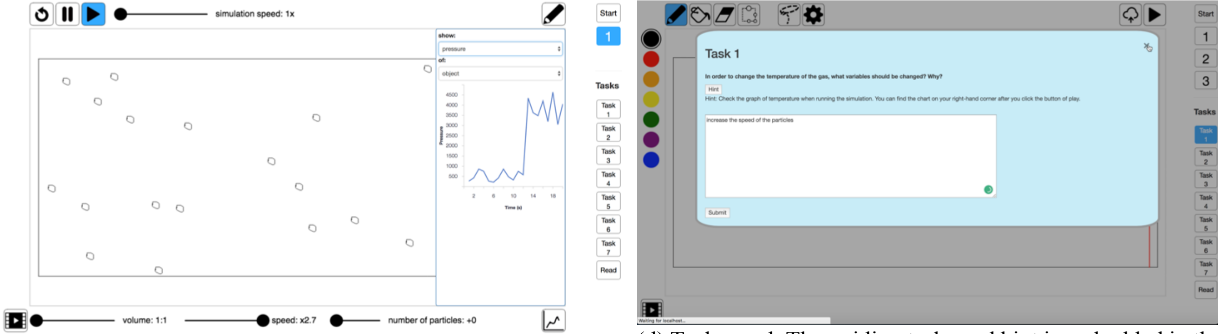
In SimSketch, there are a drawing bar, an assigning behavior bar, a run-time graph panel, and a task section (see Figure 1). We use small circles to represent the gas molecules and use sliders to control each variable. A chart is provided in SimSketch to help students discover the relations between variables. For instance, if we pull the speed slider towards the right side, the speed of molecules will increase, and there will be an increase in the diagram of the pressure as well (see Figure 1). According to the diagram, students are asked to predict, prove and explain their answers in these tasks.

Figure 1The panels in SimSketch



(a) Drawing panel in SimSketch. The drawing bar is on the top. From left to right, the functions are: pencil function, color function, erase function, define function, select function and setting. On the right side is the task section.

(b) Behavior panel: The assigning behavior is on the left side that students can assign behaviors to their drawings.



Task 1

In order to change the temperature of the gas, what variables should be changed? Why?

Hint: Check the graph of temperature when running the simulation. You can find the chart on your right-hand corner after you click the button of play.

increase the speed of the particles

(c) Run-time graph panel showing simulations. The right side is a graph panel which include a selection bar for students to choose which graphs they would like to see.

(d) Task panel. The guiding tasks and hint is embedded in the task panel.

Procedure

In this research, students worked in pairs on the tasks in SimSketch for 60 to 90 minutes, depending on students' own pace. All seven tasks should be finished, including a pre-test and a post-test. After the pre-test, the researcher gave a 5-10 minutes demonstration about how to use SimSketch. Then, students could start to finish the first three tasks without interruption. Researchers only started asking questions at the end of task 4. From task 4 to task 7, researchers would probe students for some details of their answers or their opinions.

In all these tasks, there was no sample answer provided for students. Students needed to judge their answers by themselves using SimSketch. Students were allowed to explore and answer questions by themselves, but researchers were not allowed to help students answer the task unless they had technical problems. There were some hints in each task that students can open and follow the hints. When they were writing their pre-test and posttest, students were not allowed to exchange their answers or discuss their opinions. Students were not expected to learn everything about the ideal gas law within 90 minutes. Instead, they would get acquaintance with the four variables of the ideal gas law and the microscopic view of temperature and pressure. Learning the connection between microscopic variables and macroscopic variables is what we specifically want to achieve and investigate in this research.

Data collection

Students' conversation and operations were recorded by screen recording. Under each task, students can type the answer in SimSketch task panel (Figure 1). A text file recorded their typed answers in SimSketch. Pretest and Posttest were collected right after the research. Notes were taken during the research as supplement resources for the screen recording.

Analysis

Student's conversations were transcribed and analyzed based on their understanding. According to the literature (Johnstone, 1993; Kautz et al., 2005b; Li& Black, 2016), students' utterances can be classified into three levels. The first level is macroscopic to macroscopic relationships. This level mainly includes algebraic relationships between two macroscopic variables, such as volume and pressure. The second level is macroscopic to microscopic relationships such as the number of particles and pressure or speed and temperature. Although the second level includes microscopic variables, the relationships between these variables are described as algebraic trends, which is similar to the first level. Only does the third level illustrate microscopic dynamics behind algebraic relationships. Therefore, in order to analyze students' understanding of macroscopic and microscopic perspectives of the ideal gas law, utterances were categorized regarding three levels. These three levels are complex, macroscopic to macroscopic relationships, and macroscopic to microscopic relationships. The descriptions of these three basic levels are as follow:

- Macroscopic to macroscopic relationships: The relationships between two macroscopic variables, e.g., *when volume changes, the pressure changes*.
- Macroscopic to microscopic relationships: The relationships between one macroscopic variable and one microscopic variable, e.g., *the speed of the particles will increase or decrease the temperature.*
- Complex: Involving at least three variables or potentially involving three variables in their explanations. One of the variables should be temperature or pressure, e.g., *volume has an influence due to when there is less space for the particles to move around, the pressure per individual particle increases.* In this example, students potentially indicated three variables: volume, movement, and pressure. Students described the relationship between volume and pressure with a microscopic image including variables such as space, particles and the movement of particles.

Macroscopic variables include pressure, volume, temperature, and density. Microscopic variables include speed, the frequency of collisions, the number of particles and the diameter of the particles. There are also several sublevels in the macroscopic to macroscopic relationships and the macroscopic to microscopic relationships. The complete coding scheme is shown in Appendix A.

Scoring students utterances using the category of thermodynamics allows us to check which relationships students understand and how much they understand. From their understanding level, we can trace back in which way SimSketch facilitate or inhibits students' understanding. The author scored all utterances in the first iteration and the second iteration. A second rater independently coded participants' conversation in the first iteration and the second iteration respectively. For the first iteration, the agreement between the two raters was 99.7% and Cohen's kappa of 0.92. For the second iteration, the agreement was 99.6%. The Cohen's kappa is 0.91. Both interrater reliability indicates almost perfect agreement among the raters, and thus, high confidence should be placed in the result (Landis & Koch, 1977).

Results

This section discusses our finding and answers our research questions in the following three subsections. The first subsection describes the coding results in the first iteration and second iteration respectively, along with a brief analysis of students' understanding. In the second subsection, the theme of students' conclusion is summarized, and the problems in their conclusion are discussed. The third subsection demonstrates the state of SimSketch and the details of students' learning process for the first iteration and the second iteration respectively in order to understand how students learned using SimSketch and why they formed different themes of connections.

Connection of microscopic and macroscopic variables

By counting students' utterances, it is clear that students mainly remain on describing the macro-macro and macro-micro relationships (Table 1). There are only thirteen of total complex utterances in five dyads. Students in Dyad 4 and Dyad 5 generated slightly more complicated explanation than other groups. In total, there are 51 utterances coded for the first iteration.

Table 1 The frequency of utterances in each level (complex, macro-macro and macro-micro levels) provided by students in the first iteration.

Type	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5	Total
Complex	2	1	2	3	5	13
Macro-Macro	5	5	4	3	3	20
Macro-Micro	4	5	3	4	2	18

Note: macro-macro stands for macroscopic to macroscopic relationships; macro-micro stands for macroscopic to microscopic relationships. Dyad 1 stands for the first pair of students in the first iteration. Total calculated the total number of utterances of five dyads of students in each level.

To answer the question of whether students connected microscopic variables and macroscopic variables, we analyzed students' complex utterances. For instance, students in dyad 1 explained their reason why they thought increasing the number of particles increases the pressure (R means researcher; S1.1 means student one in dyad 1; S1.2 means student two in dyad 1),

R: Would please you tell me why the pressure would be changed?

S1.1: As we saw that before, there were more particles inside. If you put more particles in (the container), there are more… moving more against like the side of the container. So…

S1.2: (Interrupt) There is more force…

S1.1: applied from (to) the inside of the container.

From their answers, we can see that students had a microscopic image in mind as the words "move against" shows that they noticed the dynamics of particles in the simulation. They connected pressure with collisions and force which applied to the container. In an expert's view, the pressure is a macroscopic variable and collisions are a microscopic variable. Hence, students in the first iteration were able to connect macroscopic variables with microscopic variables.

Table 2 The frequency of utterances in each level (complex, macro-macro and macro-micro levels) provided by students in the second iteration.

Type	Dyad 6	Dyad 7	Dyad 8	Dyad 9	Dyad 10	Total
Complex	1	3	4	6	2	16
Macro-Macro	3	2	3	2	4	14
Macro-Micro	4	4	4	3	5	20

Note: macro-macro stands for macroscopic to macroscopic relationships; macro-micro stands for macroscopic to microscopic relationships. Dyad 1 stands for the first pair of students in the first iteration. Total calculated the total number of utterances of five dyads of students in each level.

In the second iteration (**Table 2**), it is clear that students generated slightly more complex explanation (16 utterances) than those in the first iteration (13 utterances). The total number of coded utterances in the second iteration (50 utterances) is about the same as in the first iteration (51utterances). Moreover, their utterances about basic macroscopic to macroscopic relationships are less than the those in the first iteration. It is possible that students shifted moderately from the understanding of macro-level relationships to complex level, but this result needs to analyzed further.

Through further analysis, we can confirm that students in the second iteration also had abilities of connecting macroscopic variables with microscopic variables. For instance, one of students in Dyad 8 described the behavior of gas particles and associated this behavior with pressure,

R: Can I ask you to check one variable? The pressure. Do you think the pressure will change?

S8.1: Yes.

Then they operated on the simulations and chose the graph of pressure.

S8.2: But pressure does not seem to be changed a lot. But pressure just does not seem to be constant, that is because pressure only changes once particles are actually hitting the box.

This student's answer illustrated a clear micro-level dynamic of the ideal gases and included two macroscopic variables. We have the reason to believe that they were able to connect a microscopic variable with a macroscopic variable, such as hitting and pressure.

As a result, students in the first iteration and second iteration have the potential to connected macroscopic variables with macroscopic variables of the ideal gases. It seems that the lessons and SimSketch we designed were able to guide students to think from a micro-level aspect and could connect microscopic and macroscopic variables. To understand how students connected these two aspects and what problems they had, we analyzed the theme that students concluded while learning the ideal gas law.

Theme of students' complex understanding

During the lessons, students formed their complex understanding using SimSketch. Although students connected macroscopic variables with macroscopic variables of the ideal gases, their understanding was not necessarily close to what experts view because they did not have much previous knowledge. For instance, experts usually consider pressure in the kinetic model is total force per area that the particles exert by means of their collisions (Vollebregt,1967). This means the pressure is not only influenced by momentum transfer, but also by incident particle flux. However, students in our research provided researchers with incomplete understanding of temperature and pressure. Through analyzing their incomplete answers, we have an insight of how they connected the microscopic variables with macroscopic variables.

Temperature with energy

All of the students linked the temperature with speed in our research. In principle, students should have learned that temperature is proportional to the average kinetic energy from their textbook. Not all of the students could remember this connection. Only students in Dyad 5 mentioned the kinetic energy in their answers,

S5.1: So, the speed of the gas will change (the temperature).

S5.2: Yeah, so we can put in the task form.

S5.1: The speed of the gas… (typing)

S5.2: That means they have more kinetic energy.

S5.1: The speed of gas molecules affects the temperature.

S5.2: Uhm hum.

S5.1: more kinetic energy which is heat.

And concluded in their answer:

The speed of the gas molecules affects the temperature, as that means the particles have kinetic energy which is heat.

Other students either did not explain the connection between speed and temperature or only mentioned energy. As all students successfully connected speed with temperature and few complex utterances regarding in-depth discussion of temperature. As we did not expect students to mention energy in their answers, our further analysis mainly focuses on the complex relationships about pressure.

Pressure with collisions

The pressure can be considered as total fore per area that the particles exert by means of their collisions. During our research, some students connected pressure connects with collisions of particles using the word ‘collide’, ‘bouncing’, ‘hitting’, ‘move against’ and ‘bumping’, Given that students did not know the definition of pressure, these students were relatively close to the actual meaning of pressure, for example in Dyad 8, students used the words ‘collide’ and ‘bumping into each other’,

R: Could please tell why the volume decreases, the pressure will increase?

S8.2: Because again, the particles are collided more, like they are bumping into each other and it causes more pressure because they have less space to move, because they move into the container, and into each other.

Although this theme is close to the definition of the pressure, it is not complete and accurate. What collisions lead to is the forces not precisely pressure. Moreover, collisions in students’ opinion is a vague concept that may or may not include the average moment transfer and the incident particle flux.

Pressure with movement

Apart from the theme of pressure and collisions, students often indicated that pressure increases because the movement of the pressure is limited. This idea is similar to the previous one. However, students did not explicitly use the words ‘collisions’ or ‘hitting.’ They were more likely to use the words ‘move’ around or ‘to move’. For instance, Dyad 7 mentioned that less space led to the quick movement of the particles which caused higher pressure, S7.2: like the container, if you decrease the volume, then you trap the particles in a smaller area, and because it is a gas, they usually move around very quickly. So, then the pressure would be high. And that's maybe the reason I think.

Similarly, students in Dyad 4 used the same words 'move around',

S4.1: volume has an influence due to when there is less space for the particles to move around, the pressure per individual particle increases.

Students in Dyad 6 used the words 'to move',

S6.2: Yeah, so when the volume decreases, that means there is not much space for the particles to move, and then increases the pressure, because they need pressure to move. Because the movement will be limited, and pressure would be (increased).

According to these answer, it is hard to ensure whether 'move around' or 'to move' is the same as collisions, speed or simply a broad idea of the movement of particles. These words probably were synonyms for the collisions but could also be forces or energy. It is also possible that students connected pressure with movement because they mixed pressure with other microscopic variables such as collisions. Because of the ambiguity of the words used, we separated this theme from the second one (pressure with collisions). Though this theme involves uncertain interpretation, it still shows students' understanding of particles' movement in SimSketch. Students tended to think the relationships of the ideal gas law from a micro-level perspective.

Pressure with density

Another common type is pressure with density. Density is a word we summarized for students. Few of the students used the word 'density'. They often use 'compact', 'more particles in the space' or 'more particles per volume', which in our case is similar to the meaning of density. For example, students in Dyad 5 adopted words 'particles per cubic centimeter', *"when you decrease the volume of the container the temperature, density and pressure will increase. This is because a smaller volume means more particles per cm^3 meaning both pressure and density will increase,"* From our perspective, 'particles per cubic centimeter' is similar as density, but from students' perspective, they probably considered from the side of particles which is a microscopic thought.

Besides the 'particles per cubic centimeter', students also said 'compact' to indicate the distance between particles. Dyad 7 wrote, *"we think that the pressure will change if the volume of a container decreases, as it will make the particles more compact with each other, making the pressure increase."* It seems that students thought the pressure was similar to the force between particles such as repulsion so the denser the particles, the strong the pressure was.

As students thought density not as exactly what experts define, they were likely to think pressure from a microscopic perspective. They might even understand pressure as the forces between particles. Consequently, even we consider density as a macroscopic variable in the ideal gas law, we still agree that students comprehend pressure from a micro-level perspective, though they might mistake pressure as a microscopic variable such as the interactive force of particles.

Pressure with energy

This theme involves the energy and only appeared in the second iteration. According to the students' explanation, when lower the volume, the energy is more concentrate per unit area. Usually, students used 'energy' specifically in this theme. Through more in-depth analysis, we find out that the energy probably refers to as kinetic energy, since students connected with speed and mass.

Type answer: The number of particles will increase the pressure because

S9.1: Because there are more particles in the same space.

S9.2: More mass and more energy?

S9.1: more mass and therefore more energy

Later on, students discussed the relationship between speed and pressure. These two students typed: increasing the speed will have the opposite effect because speed creates more energy and thus more pressure. From their conservation, students linked speed with energy and then with pressure. It is not hard to realize that students referred to energy as kinetic energy, while they might forget the concept of kinetic energy.

There were only two dyads of students belongs to this theme, Dyad 9 and Dyad 10. However, they provided many utterances regarding pressure and energy. The reason why they generated so many utterances belonging to this theme needs a more detailed analysis.

To summarize, four out of five themes are relevant to pressure. The theme of pressure with collisions is closer to the definition of pressure. Other themes have indirect relationships with pressure, such as density and energy. According to the kinetic model, the number of particles, the volume of gas containers and the average speed of particles are all appeared in the equation of pressure. This connection means four themes are not exclusive from each other. They all described part of the pressure.

However, many dyads of students only realized one theme of pressure and stuck to this theme when learning the ideal gas law. Dyad 4, Dyad 8, and Dyad 10 included two themes of understanding in their explanation. Dyad 4 and Dyad 8 have utterances that belong to pressure with collisions, but also have utterances belongs to the theme of pressure with movement. In their opinion, ‘move around’ is probably a synonym of ‘collide’. Dyad 5 initially held the theme of pressure with density, but finally shifted to the theme of pressure with collisions. Apparently, they did not realize that both themes were incomplete and could be partially correct. Dyad 10 understood pressure as density when they explained the relationship between pressure and volume; They reasoned pressure as energy when they explained the relationship between pressure and temperature. However, students in Dyad 10 did not notice this inconsistency in their explanation. It is possible that they thought these two themes were all correct in different situations, while it does not mean that they realized each theme they mentioned were relevant and incomplete.

After analyzing students’ utterances, we wondered how students formed their theme of understanding and why most of the students stayed in only one theme of understanding. Consequently, we analyzed students learning processes of the ideal gas law to comprehend the influence of SimSketch.

Learning process

Students followed the tasks and hints to learn Boyle's law and Gay-Lussac's law. During their learning process, students discussed with their peers and manipulated on SimSketch to answer each task. By analyzing, we found out that students tended to answer their questions and test their answers by manipulating the SimSketch in both iterations. Nevertheless, we also discovered some differences between the pairs of students in the first iteration and in the second iteration due to the changes made in the second stage.

First Iteration

In this iteration, SimSketch includes all essential functions such as a drawing bar, an assigning behavior bar, a simulation section, a graph panel and a task section. After a short introduction, all five dyads of students were able to manipulate and explore SimSketch themselves. According to the guiding tasks and hints, these five dyads all tested their hypothesis or proved their answers by either looking at the variation in the graphs or comparing the values from the graphs before and after their manipulation. For instance, students in Dyad 1 gave their hypotheses and tested them using SimSketch in task 3,

[Two students checked the variables shown on the selection bar above graphs]

S1.1: Here's density, collisions, pressure…

S1.2: Collisions probably?

S1.1: Density will increase. Collisions will increase. That's good?

[They typed their predictions in task 3: hypothesis Density - will increase; Collisions - will increase.]

[They drew 3 particles and set the number to 20 for each drawing, and also set speed as 5. After running the simulation, they decreased the volume, and opened the graph of density.]

S1.1: Density. Density is like this…[the density increased in the graph]

S1.2: Oh, yeah. So, proved.

S1.1: Density and ?

S1.2: So, density. This is it.

S1.2: Like, collisions?

[They clicked the graph of collisions and changed the volume again]

S1.2: Collisions as well.

Not only did students in Dyad 1 testing their hypotheses using SimSketch, all the other did more or less the same. They found the variables from the selection bar above the graphs. Based on this bar, students guessed which variables would be affected if volume decreased. By using SimSketch, they were able to test and proved their answers.

Furthermore, all students in the first iteration successfully connected speed with temperature by changing the speed in the simulation and observing the variations in graphs. However, only dyad 5 mentioned that kinetic energy might be related to heat and thus temperature in task 1. Dyad 5 is also the only group using the expression of "speed/temperature" in their answers, showing that they clearly understood that the change of the speed means the change of the temperature of the ideal gases. Although other dyads of students did not state that temperature is closely related to speed, most of them (4/5 dyads) did apply this knowledge while reproducing the Gay-Lussac's law on SimSketch in task 5.

Unlike the relationship between speed and temperature that students could directly manipulate the speed and saw the change of temperature in graphs, the connection between collisions and pressure was rather inexplicit in SimSketch as we expected students to compare the graph of collisions and the graph of pressure carefully. However, comparing graphs was not the only method to reveal the micro-macro relationships between collisions and pressure. Dyad 1 only noticed the existence of the graph of collisions in task 2 but still linked collisions with pressure without comparing graphs later on. Dyad 4 and Dyad 5 gave their first complex reasoning through discussion with each other and observation on the simulations. Dyad 5 did not even find the graph of collisions, but they shifted their ideas by discussing with each other,

R: Why do you think the pressure will change?

S5.2: Because… the pressure will change because when you pump more air in, it means there are more particles per cm, per volume, which means that pressure would increase, because more particles make…the definition of the criteria is that when there are more particles means more pressure

R: The pressure is density of particles?

S5.2: Yes, denser…

S5.1: (Interrupted) The pressure is cause by particles hitting the walls. More particles more hitting the wall of the area.

R: Can you show me (in SimSketch)?

[They operated on SimSketch]

S5.2: Yeah, and run it.

S5.1: Pressure… (find pressure)

S5.2: So, we see pressure. And wait for it until it is stabilized.

R: So, how do you understand if it is not stabilized?

S5.2: I guess it is because the pressure is measurable, say you will have a sensor, and then it will measure how many particles or how hard are particles hitting the wall of the sensor, and it also depends on the position of the particles. If there are more particles towards one side, then the other displaced the sensor noticed kind of more or less difference. That’s why we see a kind of deviation up and down.

The two students in Dyad 5 exchanged their guessing about pressure and one of them shifted the explanation for pressure from density to collisions. He used the word ‘hitting’ as his peer students mentioned. It is possible that he was inspired by his peer students and changed his mind.

According to our analysis, it seems that even though students did not behave as we expected, some of them could still grasp the idea that the collisions of particles is relevant to the pressure from various representations in SimSketch. The inexplicit relationship even stimulated students to discuss and guess more about pressure. Nevertheless, this may explain the reason why most students did not use the proper word “collisions” to describe the behavior of the ideal gases. Additionally, Dyad 2 and Dyad 3 noticed the graph of collisions as Dyad1, but their understanding for the pressure was completely different. Dyad 2 and Dyad 3 did not consider that collisions would have any relationship with pressure. When students in Dyad 2 accidentally found out the similarities between the graph of collisions and the graph of pressure, they explained their doubts to researchers but then attracted by another phenomenon and did not continue this discussion.

S2.2: Pressure is really similar to the collisions.

R: Can I ask why the collisions is similar to the pressure?

S2.2: The graph is very similar, like every time the particle bump into the wall, the pressure went up then, yeah, it was really regular.

S2.1: Look the temperature! It is 100.

Although Dyad 2 and Dyad 3 did not connect collisions with pressure, they connected pressure with density. Because these two groups of students mentioned in their pretest that pressure was related to the concentration of particles and tightness of particles, they might be inspired by the variable of density shown in selection bar and then reinforced their previous guessing about pressure. In addition, the answers in task 3 and task 4 were include both collisions and density. As a result, students who held the idea that pressure was connected to density could not find evidence to reject their ideas. Due to this situation, we considered to made some changes in the guiding tasks.

Second Iteration

Based on students ‘feedback in task 6 in the first iteration, we added a slider function to copy more identical drawings in the simulations. Therefore, students could add more particles while running the simulation instead of going back to reset behavior icons. The new function made manipulation of SimSketch more convenient and saved some time for students. Apart from improving user experience, we revised some questions in the tasks to make it clearer for students, for example, we substituted “why” as “please explain your reason behind” and replace the question “please explain the Boyle’s law and Gay-Lussac’s law” to several “why” questions. Although controlling variables is not the purpose of our research, it is an essential knowledge regarding the ideal gas law. Considering students always stated that decreasing the volume increases the pressure, forgetting to mention that this relationship held when the temperature and the number of particles remained unchanged, we included a table to draw students' attention about the conditions. Since this table did not include micro-level variables such as collisions and speed, we expected students would encounter more conflictions when filling in the table and thus provided more complex understanding.

Additionally, we changed task 4 to make the tasks more consistent. Task 4 was intended to guide students to learn the relationship between the number of particles and pressure. However, according to our observation in the first iteration, this relationship could not help students to reject the ideas that pressure was related to density. Hence, we changed task 4 to guide students to connect pressure with collisions and to understand Gay-Lussac's law better.

In the second iteration, all five dyads finished the first three tasks with more or less the same processes as students in the first iteration. They all checked the graphs and manipulated the simulations in order to answer each task. Similar to the first iteration, students were able to connect speed to temperature and even indicated that the temperature has connection to energy or heat in the task 1. Nevertheless, none dyads of students paid attention to the graph of collisions. Only Dyad 8 inspired by the collisions shown on the graph and then successfully connected collisions to pressure, which is even less than the first iteration. Although other dyads did not link collisions to pressure, most of them did give nice explanation for collisions.

Comparing to the first iteration, students did not provide more complex understanding in the second iteration. It seems that the changes did not stimulate students to think more deeply. Students did answer all "why" questions, and they did discuss more when filling in the table.

However, during their discussion, they only talked about the meaning of tables rather than speed or collisions. In task 4, although most of students did not mentioned density in their conclusions, they still did not connect pressure with collisions instead some of them connected pressure with energy. This connection might stem from the modification of task 1. For instance, after Dyad 9 mentioned that more speed meant more energy in task 1, they applied energy in various relationships that might be relevant to pressure as well. They wrote in the task 2: "*All three factors affect pressure, increasing the volume will decrease the pressure, because there is less energy per unit area. Increasing the speed will have the opposite effect because speed creates more energy and thus more pressure. The number of particles will increase the pressure because there is more mass and therefore more energy.*" This may explain why Dyad 9 had more complex understanding than others.

However, when explaining the meaning of pressure, student S9.2 again said: *pressure is how much force there is for every unit area. So, if there is same force, but then have same energy… but then a lower volume, (there is more pressure) because there is more energy*.It is clear that they understood pressure in a macro-level, but when connecting to micro-level, they tended to connect it with the concept they knew. The lack of knowledge of linear momentum could be one of the reason, while the flaw of the representation in the simulation might influence their understanding as well. For instance, students in Dyad 9 thought the overlapping of the particles caused the unstable deviation in the graph of the pressure,

R: But why is it fluctuated?

[R showed the graph by drawing one particle and ran it]

S9.2: Oh, why does it go up and down?

R: Yeah!

S9.2: I think because some particles...It depends on how they spread out. Because some particles go side of each other, like they overlap.

The overlap of drawing in simulation happened quick often. It is a limitation of this simulation but it is not the reason why the variation in the graph of pressure was fluctuated. Students falsely associated the graph with the limitation shown in SimSketch. It implies that the representation of the movement of particles in the simulation affects students' understanding.

Conclusion

Our research focuses on how students learn to connect the macroscopic and microscopic variables of the ideal gas law using the drawing-based modeling (SimSketch). We developed an educational game in SimSketch for students to learn the ideal gas law and analyzed students' operation, discussions, and their written answers.

Whether students connected macroscopic and microscopic variables

As examples shown above, students did connect the macroscopic variables with microscopic variables of the ideal gas law. All of them were able to connect speed with temperature. From the utterances that were coded as complex, we can see that students connected pressure with collisions. Although not of students connected pressure with collisions, they connected pressure with other variables that still illustrated their microscopic perspective understanding of the ideal gases.

How students connected macroscopic and microscopic variables

Students connected macroscopic variables with microscopic variables in different ways. Excluding the connection between temperature and energy, we summarized four themes of students' connections: pressure with collisions; pressure with movement; pressure with density; pressure with energy. Only the pressure-collisions theme meets our expectation. Other themes are not necessarily wrong. These are the incomplete understanding of pressure. There are some connections between these four themes, but students did not consider these connections. Instead, most of them stuck into one theme during their learning. Since not all of the students had learned the concept of pressure before, these themes were more likely to be formed by using SimSketch.

How students learned to connect macroscopic and macroscopic variables using SimSketch

In order to understand how students learned connections between micro-level and macro-level, we analyzed students' operations while learning the ideal gas law and found out that students used SimSketch to test their hypothesis. By testing, they connected certain relationships of the ideal gas law.

Students also learned to connected temperature and speed by manipulating the speed and observed the changes in graphs. It is possible that by manipulating SimSketch, students were able to connect macroscopic and microscopic variables.

Moreover, through discussions with each other, they provide interesting and meaningful conversations. Some of the students changed their ideas about pressure and some of them concluded that pressure was related to collisions after their discussion. Therefore, we believe that students learned to connected variables by discussion as well.

The choice of the representations in SimSketch may also influence students'learning. In both iterations, all students connected temperature with speed. It seems evident for students to connect temperature and speed by manipulating SimSketch. However, this explicit representation did not stimulate students to provide interesting or meaningful conversations. As for the inexplicit representations of pressure and collision, we expected students to notice the frequency of collisions in the graph panel, as the frequency of collisions graph always shows a similar variation to the pressure graph. Nevertheless, no matter in which iteration, most dyads did not compare the graph of collisions with the graph of pressure. Some of them did not even notice the graph of collisions. Only a few of students noticed it and then successfully connected it with pressure. These small number of students adopted the words “collide” or “hit” to interpret pressure on a micro-level. Others who did not use the words ‘collisions’ or ‘hit’ might gain their microscopic view by guessing and discussing with their partner. It seems that inexplicit representations did not guide students to connect variables as we expected but facilitated students to discuss more in-depth.

Furthermore, students who connected pressure with density were likely to be influenced by the representations of graphs in SimSketch as students frequently clicked the density graph. Although we changed the guiding tasks in the second iteration, some students still connected pressure with density. It seems that the density graph reinforced their guessing or previous knowledge.

As Gulyas and Kampis (2015) indicated representations in simulations matter how people understand the problem. Although the models (representations) in simulations represent reality, they do not depict the real phenomena. There are always involved simplifications. These simplified models in simulations affect the quality of the simulations. Some forms of representations are easier for people to understand than the others (Gulyas & Kampis, 2015).

Besides representations, the limitations of SimSketch may deter students’ learning. The overlap of drawings is one limitation of SimSktech. Some students thought it was the reason why the graph of pressure was unstable, though this unstable variation had nothing to do with the overlap of drawings. In this case, students could not understand the graph of pressure or learn to connect variables as we expected due to this limitation of SimSketch.

Guiding tasks also played a significant role in guiding students to grasp the new knowledge of the ideal gas law. The tasks in this research were designed on a base of model-based learning. Students did not have difficulties following these tasks. They were able to give their predictions and modify their predictions. However, the words and questions used in these tasks were influenced students' learning. For example, in the second iteration, the changes in task 1 made students think about energy all the time. One dyad explained every relationship of the ideal gases using energy, though they gave the complex utterances more than others. The proper scaffolding leads to better understanding of the phenomenon (Kukkonen et al., 2014). Without scaffoldings, it is hard to say whether students will still be able to learn to connection macroscopic and microscopic variables (Heijnes, 2017; Kukkonen et al., 2014).

Recommendations and Suggestions

SimSketch is rather easy for students to use. All students in this research did not waste time on searching or exploring the functions in it. Allowing students to draw things in SimSketch made students interested to play around with it. They also understood what they drew were represented for gas particles. Some even related their drawing to real-life contexts, such as the oxygen and nitrogen gas particles in balloons or in a container. SimSketch seems a very promising modeling tool for students to learn the ideal laws, but there are some improvements the programmers can make.

In order to improve the demonstration of collisions, a sensor can be introduced in the simulation to show the collide between particles and the sensor, along with the link to pressure. Programmers can also add a behavior called collisions for helping students to realize the collisions between particles and walls.

Although making students realize the controlled variables in the Boyle's las and Gay-Lussac's law is not the focus of this research, they are essentials to understand the ideal gas law. However, the existing SimSketch does not emphasize this. Maybe the following programmers can add more configurations to indicate different laws and aspects of the ideal gas law.

Tasks can be helpful to guide students to learn certain concepts. Unfortunately, the tasks designed in this research embedded in SimSketch, which means it is not possible for teachers to change. We expect to improve SimSketch to allow teachers to upload their tasks in the future.

Apart from simulation, we should be careful about the words used in tasks. If the questions are too simple, such as "why?", Students may not pay attention to it. On the opposite, some questions may mislead students to understand the concepts in one direction because of the question. It is hard to avoid misleading tasks, but teachers can indicate it while students are doing the tasks or afterward.

Mentioning teachers, interacting with each pair of students in a whole classroom is idealistic. It may be hard for teachers to motivate a whole class of students to give in-depth understanding or reasoning. "Why" questions can be directly used for small samples in research, but in a classroom, it is not hard to imagine that only a few students would answer the questions. Others may only listen to it. For further research, more investigation about how to implement the drawing-based modeling in a whole class can be conducted.

Drawing-based modeling has its advantages of using students' drawing. Students in this research did not have problems with drawings. However, how drawings or sketches in the modeling tools influence students' understanding, and how drawings influence students to form their models remain unknown. In the future, it will be interesting to study these questions. So far, students can only draw simple sketches in the drawing-based modeling. By more trails and research, there will be more useful functions and more possibilities for students and teachers to use this modeling tool.

References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. Learning and Instruction, 16(3), pp.183-198.

Besson, U. (2001). Work and energy in the presence of friction: the need for a mesoscopic analysis. European Journal of Physics, 22(6), pp.613-622.

Bollen, L., and van Joolingen, W. (2013). SimSketch: Multiagent Simulations Based on Learner-Created Sketches for Early Science Education. IEEE Transactions On Learning Technologies, 6(3), 208-216.DOI: 10.1109/tlt.2013.9.

Bowen-Jones, M. and Homer, D. (2014) Physics Course Companion. Oxford IB diploma programme, 1st edition.

Chabay, Ruth W. and Sherwood, Bruce A. (1999) Bringing atoms into first-year physics, American Journal of Physics 67, 1045-1050; https://doi.org/10.1119/1.19180

De Jong,T. Van Joolingen, W. (1998) Scientific discovery learning with computer simulations of conceptual domains. Rev Educ Res 68: 179–201

Eylon, B., & Uri, G. (1990). Macro-micro relationships: The missing link between electrostics and electrodynamics in students' reasoning. Int. J. Sci. Educ., 12(1), 79-94. from http://dx.doi.org/10.1080/0950069900120107

Fretz, E.B., H.-K. Wu, B. Zhang, E.A. Davis, J.S. Krajcik, and E. Soloway. (2002) An investigation of software scaffolds supporting modeling practices. Research in Science Education 32, no. 4: 567–89.

Grosslight, L., Chr. Unger, E. Jay, and C.L. Smith. (1991) Understanding models and their use in science: Conceptions of middle and high school students and experts. Journal of Research in Science Teaching 28, no. 9: 799–822.

Gulyas, L. and Kampis, G.(2015) Models, Representations and Comparisons in Computer Simulations. Procedia Computer Science, 66, 5-12. DOI: 10.1016/j.procs.2015.11.003

Hansen, J., Barnett, M., MaKinster, J. and Keating, T. (2004). The impact of three ‐ dimensional computational modeling on student understanding of astronomy concepts: a qualitative analysis. International Journal of Science Education, 26(13), pp.1555-1575.

Heijnes, D., van Joolingen, W. and Leenaars, F. (2017). Stimulating Scientific Reasoning with Drawing-Based Modeling. Journal of Science Education and Technology, 27(1), pp.45-56.

Johnstone A. H., (1993), The development of chemistry teaching, J. Chem. Educ., 70, 701-704.

Kautz, C., Heron, P., Loverude, M., and McDermott, L. (2005a). Student understanding of the ideal gas law, Part I: A macroscopic perspective. American Journal Of Physics, 73(11), 1055-1063. http://dx.doi.org/10.1119/1.2049286

Kautz, C., Heron, P., Shaffer, P., and McDermott, L. (2005b). Student understanding of the ideal gas law, Part II: A microscopic perspective. American Journal Of Physics, 73(11), 1064-1071. http://dx.doi.org/10.1119/1.2060715.

Kukkonen,J.E., Kärkkäinen, K., Dillon, P & Keinonen, T (2014) The Effects of Scaffolded Simulation-Based Inquiry Learning on Fifth-Graders' Representations of the Greenhouse Effect, International Journal of Science Education, 36:3, 406-424, DOI: 10.1080/09500693.2013.782452

Landis, J.R. and Koch, G.G. (1977) The Measurement of Observer Agreement for Categorical Data. Biometric, 33, 159-174. http://dx.doi.org/10.2307/2529310

Li, N. and Black, J.B.(2016) Inter-level scaffolding and sequences of representational activities in teaching a chemical system with graphical simulations. J Sci Educ Technol 12: 715-730. DOI:10.1007/s10956-016-9262-4

Liang, J. Chou, C. and Chiu, M. (2011) Student test performances on behavior of gas particles and mismatch of teacher predictions. Chemistry Education Research and Practice, 12, 238–250. DOI: 10.1039/C1RP90029C

Lin, H., and Cheng, H. (2000) The Assessment of Students and Teachers' Understanding of Gas Laws. Journal of Chemical Education. Vol.77(2), 235-238.

Louca, L., and Zacharia, Z. (2012). Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. Educational Review, 64(4), 471-492. http://dx.doi.org/10.1080/00131911.2011.628748

Lucas, A. (2014) Connecting microscopic physics with the macroscopic properties of materials in introductory physics courses. Harvard University (2), 1-2.

Loverude, M., Kautz, C., & Heron, P. (2002). Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas. American Journal Of Physics, 70(2), 137-148. http://dx.doi.org/10.1119/1.1417532

Madden, P.S., Jones, L.L., and Rahm, J. (2011) The role of multiple representations in the understanding of ideal gas problems. Chemisrty Education Research and Practice, 12, 283-293.

McKagan, S., Perkins, K., Dubson, M., Malley, C., Reid, S., LeMaster, R. and Wieman, C. (2008). Developing and researching PhET simulations for teaching quantum mechanics. American Journal of Physics, 76(4), pp.406-417.

Miller, R., Ogborn, J., Briggs, J., Brough, D., Bliss, J., Boohan, R., Brosnan, T., Mellar, H., & Sakonidis, B. (1993). Educational tools for computational modelling. Computers & education, 21(3), 205–262.

Morris, P.(2015) Physics for the IB MYP 4 & 5: By Concept. Hodder Education, p222.

Quillin, K. and Thomas, S (2015) Drawing-to-Learn: A Framework for Using Drawings to Promote Model-Based Reasoning in Biology, CBE–Life Sciences Education Vol. 14, 1–16, DOI:10.1187/cbe.14-08-0128

Russell, J., Kozma, R., Becker, D., and Susskind, T. (2000) SMV: Chem: Synchronized multiple visualizations in chemistry. Wiley, New York.

Schmalz, H. (2012). Drawing based modeling and simulation in primary school science education - The impact on students' attitude towards science and domain specific knowledge.

Treagust, D., Chittleborough, G., & Mamiala, T. (2002). Students' understanding of the role of scientific models in learning science. International Journal Of Science Education, 24(4), 357-368. DOI: dx.doi.org/10.1080/09500690110066485

Van Joolingen, W., Aukes, A., Gijlers, H., & Bollen, L. (2014). Understanding Elementary Astronomy by Making Drawing-Based Models. Journal Of Science Education And Technology, 24(2-3), 256-264. DOI: 10.1007/s10956-014-9540-6

Vollebregt, M.J. (1967) A problem posing approach to teaching an initial particle model. Centre for Science and Mathematics Education, Utrecht University, Utrech, The Netherlands, pp.105.

Wieman, C., Adams, W., & Perkins, K. (2008). PHYSICS: PhET: Simulations That Enhance Learning. Science, 322(5902), 682-683. DOI: dx.doi.org/10.1126/science.1161948

Wouters P. (2017) Modeling and Worked Examples in Game-Based Learning. In: Wouters P., van Oostendorp H. (eds) Instructional Techniques to Facilitate Learning and Motivation of Serious Games. Advances in Game-Based Learning. Springer, Cham DOI: doi.org/10.1007/978-3-319-39298-1_10

Young, H and Freedman, R.A. (2012) University Physics Plus Modern Physics. Pearson Education, 13th ed.

Appendix

Coding Scheme

Category	Relationships	Understanding level	Description	Example
Complex			Involving at least three variables or potentially involving three variables in their explanations. One of the variables should be temperature or pressure.	e.g. Volume has an influence due to when there is less space for the particles to move around the pressure per individual particle increases
Macroscopic to Macroscopic relationships	V-p	V-p superficial	Students only indicate two factors are related, but do not indicate the trends.	e.g. when volume changes, the pressure changes.
		V-p deep	Students mention two factors and the trends of their relationship.	e.g. when volume decreases, the pressure increases.
		V-p deep. c	Students do not only mention the variation trends between two V and P, but also include or potentially include the constant conditions.	e.g. volume decreases, the pressure will increase, the number of particles and temperature remain constant.
	T-p	T-p superficial	Students simply indicate T and P are related.	e.g. Temperature affects.
		T-p deep	Students mention two factors and the trends of their relationship	e.g. Increase the Temperature

		T-p deep .c	Students do not only mention the variation trends and factors, but also include or potentially include the constant conditions.	e.g. J: so basically, when the temperature is the same. K: and the number of particles in the gas is also the same. J: And pressure times the volume is the same.
	ρ-p	ρ-p superficial	Students only indicate that density changes with pressure.	
		ρ-p deep	Students do not only indicate factors like density and pressure, but also indicate the variation trends between them	
		ρ-p deep .c	Students indicate that pressure will increase if density increases and also mention other variables.	
	ρ-V	ρ-V superficial	Students simply indicate density and pressure are related.	
		ρ-V deep	Students mention two factors and the trends of their relationship.	
		ρ-V deep .c	Students do not only mention the variation trends and factors, but also include or potentially include the constant conditions.	
Macroscopic to Microscopic relationships	n-p	n-p superficial	Students only indicate that pressure changes with the number of particles.	e.g. when the number of particles changes, the pressure changes.
		n-p deep	Students mention two factors and the trends of their relationship.	e.g. when the number of particles increases, the pressure increases.
	n-ρ	n-ρ superficial	Students only indicate two factors are related, but do not indicate the trends.	
		n-ρ deep	Students mention two factors and the trends of their relationship.	
	C-p	C-p superficial	Students only indicate that two factors are related, but do not indicate the trends	
		C-p deep	Students mention two factors and the trends of their relationship.	

s-p	s-p superficial	Students only indicate that two factors are related, but do not indicate the trends
	s-p deep	Students mention two factors and the trends of their relationship.
r-p	r-p superficial	Students only indicate that two factors are related, but do not indicate the trends
	r-p deep	Students mention two factors and the trends of their relationship.
s-T	s-T superficial	Students only indicate that two factors are related, but do not indicate the trends
	s-T deep	Students mention two factors and the trends of their relationship.
V-C	V-C superficial	Students only indicate that two factors are related, but do not indicate the trends
	V-C deep	Students mention two factors and the trends of their relationship.

Pretest

What are the properties of gas? Can you draw them?

Could you please tell me something about pressure, volume, temperature and number of particles? What are the relation between these variables?

Guiding Tasks in the First Iteration

Task 1

In order to change the temperature of the gas, what variables should be changed? Why?

(Hint: Check the graph of temperature when running the simulation. You can find the chart on your right-hand corner after you click the button of play.)

Task 2

Please try to increase the pressure using as many methods as you can, and give your conclusions about which variables related to pressure. Please explain your reasons.

(Hint: change different variables such as speed and volume, and then check the change of the pressure.)

Task 3

If we decrease the volume of a container, please predict what variables will change and explain whether they will increase or decrease.

Please write down your prediction below:

Try to prove your prediction on Simsketch, and please explain whether you were correct or not

Task 4

If we pump in air in the container, please predict what properties will change.

Please try on Simsketch and correct your answer below

Task 5

Please read the following text, and try to demonstrate Boyle’s and Gay-Lussac’s law on Simsketch.

Boyle's Law

In 1662 Robert Boyle studied the relationship between volume and pressure of a gas at constant temperature. He observed that volume of a given mass of a gas is inversely proportional to its pressure provided the temperature remains constant. Boyle's law, published in 1662, states that, at constant temperature, the product of the pressure and volume of a given mass of an ideal gas in a closed system is always constant. It can be verified experimentally using a pressure gauge and a variable volume container. It can also be derived from the kinetic theory of gases: if a container, with a fixed number of molecules inside, is reduced in volume, more molecules will strike a given area of the sides of the container per unit time, causing a greater pressure. A statement of Boyle 's law is as follows: The volume of a given mass of a gas is inversely related to the pressure exerted on it at a given temperature and given number of moles. The concept can be represented with these formulae:

$$PV = k$$

or

$$p_1V_1=p_2V_2$$

where P is the pressure, and V is the volume of a gas, and k1 is the constant in this equation (and is not the same as the proportionality constants in the other equations below).

Gay-Lussac's law

Gay-Lussac's law, Amontons' law or the pressure law was found by Joseph Louis Gay-Lussac in 1809. It states that, for a given mass and constant volume of an ideal gas, the pressure exerted on the sides of its container is directly proportional to its absolute temperature. As a mathematical equation, Gay-Lussac's law is written as either:

$p/T=k$

or

$p_1/T_1=p_2/T_2$

where P is the pressure, T is the absolute temperature, and k is another proportionality constant.

Task 6

1. What limitations do you find in the Simsketch?

2. Can you compare the gas show on the Simsketch with the gas we see in our real life?

Task 7

1. Is there one law that can combine Boyle's and Gay-Lussac's law? Why?

2. What variables can describe the microscopic scale of molecules?

Guiding Tasks in the Second Iteration

Task 1

In order to change the temperature of the gas, what variables should be changed? Can you explain the reason behind?

(Hint: Check the graph of temperature when running the simulation. You can find the chart on your right-hand corner after you click the button of play.)

Task 2

Please try to increase the pressure using as many methods as you can, and give your conclusions about which variables related to pressure. Please explain your reasons.

(Hint: change different variables such as speed and volume, and then check the change of the pressure.)

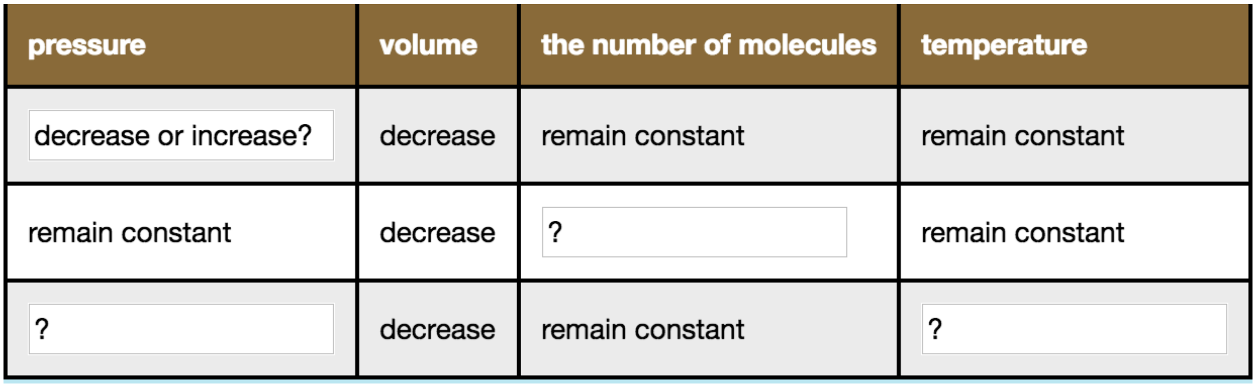
Is that possible to change other variables, but keep the average pressure more or less unchanged?

Task 3

If we decrease the volume of a container, please predict what variables will change and explain whether they will increase or decrease.

Please write down your prediction below:

Try to prove your prediction on Simsketch, and fill in the table below



pressure	volume	the number of molecules	temperature
decrease or increase?	decrease	remain constant	remain constant
remain constant	decrease	?	remain constant
?	decrease	remain constant	?

Task 4

If we heat up the container, please predict what properties will change.

Please try on Simsketch and correct your answer below

Task 5

Please read the following text, and try to demonstrate Boyle’s and Gay-Lussac’s law on Simsketch.

Boyle's Law

In 1662 Robert Boyle studied the relationship between volume and pressure of a gas at constant temperature. He observed that volume of a given mass of a gas is inversely proportional to its pressure provided the temperature remains constant. Boyle's law, published in 1662, states that, at constant temperature, the product of the pressure and volume of a given mass of an ideal gas in a closed system is always constant. It can be verified experimentally using a pressure gauge and a variable volume container. It can also be derived from the kinetic theory of gases: if a container, with a fixed number of molecules inside, is reduced in volume, more molecules will strike a given area of the sides of the container per unit time, causing a greater pressure. A statement of Boyle 's law is as follows: The volume of a given mass of a gas is inversely related to the pressure exerted on it at a given temperature and given number of moles. The concept can be represented with these formulae:

$$PV = k$$

or

$$p_1V_1=p_2V_2$$

where P is the pressure, and V is the volume of a gas, and k1 is the constant in this equation (and is not the same as the proportionality constants in the other equations below).

Gay-Lussac's law

Gay-Lussac's law, Amontons' law or the pressure law was found by Joseph Louis Gay-Lussac in 1809. It states that, for a given mass and constant volume of an

ideal gas, the pressure exerted on the sides of its container is directly proportional to its absolute temperature. As a mathematical equation, Gay-Lussac's law is written as either: $p/T=k$ or $p_1/T_1=p_2/T_2$ where P is the pressure, T is the absolute temperature, and k is another proportionality constant.	

Task 6

1. What limitations do you find in the Simsketch?

2. Can you compare the gas show on the Simsketch with the gas we see in our real life?

Task 7

1. Is there one law that can combine Boyle's and Gay-Lussac's law? Why?

2. What variables can describe the microscopic scale of molecules?

Posttest

A weather balloon is a balloon which carries instruments aloft. These instruments are called radiosondes. They can detect atmospheric pressure, temperature, humidity and wind speed. The weather balloon is usually filled with hydrogen or helium. The ascent rate can be controlled by the amount of gas with which the balloon is filled. By trapping the helium inside a balloon, we can attach a line to the balloon, called the flight train, with our instruments suspended at the other end (see figure 1). The balloon will then lift our instruments to the edge of space and stay at a constant altitude for long periods of time.

Figure 2 weather balloon

Weather balloon are quite useful for weather forecasting or diagnose current environment condition. About 800 locations around the globe do routine release twice a day. A weather balloon may reach altitudes of 40 km (25 miles). At this altitude, the pressure of atmosphere is approximately 18 820pa (the pressure is proximately 101 325pa near the ground) and the temperature of atmosphere is approximately -57°C (the temperature is about 15°C near the ground).

Q: According to the information above, please draft the gas in the balloon when it is near the ground and when it reaches 40km. How do the variables about the gas in balloon change?

Q: If the weather balloon flies higher, can you predict what will happen to the balloon?

The Analysis of Pretest

	Dyad 1	Dyad 2	Dyad 3	Dyad 4	Dyad 5	Dyad 6	Dyad 7	Dyad 8	Dyad 9	Dyad 10
Pressure	p-d	p-d	p-d	p-d; p-force/area	p-n; p-force/area	p-d	Nah	somthing happening to object; p-d	p-force/area	Nah
Temperature	Nah	hotness/coldness	collisions; speed	Nah	energy	Nah	Nah	hot/cold; amount of heat	heat	Nah

p-d: pressure with density

p-force/area: students indicated that pressure is the force per area.

Nah: students did not give answer or wrote “don’t know”