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Sensemaking using computer simulations as a pedagogical tool in a university chemistry course

A qualitative analysis of episodes of student discussion

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Abstract

Science education has moved beyond factual recall and memorization of laws and principles to become a process of integrating students into the practice of science as a discipline. The shift towards inquiry as the means of constructing knowledge has led research into the many facets of how students make sense of science. With interactive technology becoming prevent within science education, this study seeks to understand the processes through which computer simulations aid students in their sensemaking using the epistemic games framework. This was done by describing how students discuss and work to solve real-world based problems through interactions with computer simulations while analysing the affordances simulations offered the students in this sensemaking process. This study analysed student discussions centred on collaboratively working on an inquiry-based activity worksheet set within real-world contexts. The study employed qualitative analysis to identify and analyse episodes within student discussions that featured rich sensemaking discussions and the use of the affordances of the computer simulations. Findings indicate that students engaged in multiple episodes of sensemaking drawing on resources from the worksheet, prior knowledge and the affordances of the simulation. Students engaged in robust explanation building with the fluent use of mechanistic reasoning while using scientific theories, real-world information and analogical thinking. It was also found that students used the simulation output as fact and as a representation of authority along with using it as a resource for sensemaking. The study also found instances of incorrect reasoning, use of incorrect facts and the application of alternate conceptions in the students' sensemaking episodes, which showed the difference between sensemaking and conceptual understanding. This research indicated that simulations can be used as a tool to stimulate sensemaking in chemistry courses in the university, while highlighting the importance of guidance and scaffolding by teachers and designers to effectively use computer simulations as aids in scientific sensemaking.

Key words: Sensemaking, Computer Simulation, Inquiry Learning, Chemistry Education.

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1 Introduction

For decades, science education was often presented as a rhetoric of conclusions, where students were expected to memorize finished bodies of knowledge rather than understand the process of inquiry (Osborne, 2001). In this traditional model of science education, the focus remained on vocabulary and memorisation of facts, which frequently resulted in "inert knowledge" (Ford, 2012) which resulted in a student possessing information but who could not apply it to understand real-world phenomena. In these traditional settings, the teacher typically functioned as the sole provider of knowledge, while students acted as passive recipients. Scientific claims were often accepted at face value without the critical scrutiny that defines actual scientific practice (Osborne, 2001).

In recent times science education has shifted to place students as participants in the actual practices of the discipline. To move away from passive reception, educators have embraced active learning, defined by Chi and Wylie (2014) as active cognitive engagement detected through overt student behaviours. In this paradigm, science education concerns itself with teaching science as a practice and learning takes place by students replicating the work of scientists as practitioners of the discipline (Ford, 2008). An important strand of this evolution is the move towards inquiry-based learning, which allows students to construct knowledge through methods similar to those of professional scientists (Pedaste et al., 2015). Inquiry learning is a type of active learning process where students discover new causal relations by formulating hypotheses and testing them through observations and experiments (Pedaste et al., 2015).

In this formulation of inquiry-based learning, it is important to note that the knowledge students create is usually new and thus in some ways, students are similar to a scientist who encounters a new problem (Kapon, 2017). In this regard, previous research suggests that scientists and non-scientists interpret scientific claims quite differently, reflecting differences in their practices. Scientists tend to take a more cautious, critical approach as they work to understand the claims, whereas non-scientists are more likely to accept them at face value (Ford, 2012). Thus, one difference that inquiry learning ought to incorporate is teaching for making sense of the world in a scientific way. This indicates that scientific sensemaking should be an important aspect of inquiry learning, as a means of developing practices which make sense of the natural world in a scientific manner.

A further link between scientific sensemaking and inquiry learning is the notion of vexing questions. Research has shown that question-asking is an authentic science skill that promotes deep learning (Odden & Russ, 2019b). Question-asking drives the process of inquiry through being a motivational factor as certain questions feel compelling enough for students to want to address gaps or inconsistencies in their knowledge (Odden & Russ, 2019b). Scientific sensemaking is also often triggered by "vexing questions" (Odden & Russ, 2019b, pp. 1062) which are questions that arise when intuitive knowledge clashes with scientific observations. Therefore, we can see that student sensemaking and inquiry learning are linked, indicating that a grasp of practice of scientific sensemaking is a necessary fact of inquiry learning in science (Ford, 2012). Further, when multiple representations are important within the subject matter, such as in the subject of chemistry, making sense of these disparate yet linked representations is an important aspect of the grasp of practice that is necessary for inquiry (Plass et al., 2012).

This concept of representational competence (the ability to move between different levels of describing concepts) becomes part a suite of tools required to make sense of chemistry. As Gabel (1993) argues, students encounter chemical phenomena through a series of different levels of representations. At the start of their studies, students meet descriptions of chemical phenomena at the observable or macroscopic level, which is how they experience chemistry in their lives. However, in later classes, the explanations of these phenomena use the representations of atoms and molecules, which are at the sub microscopic level. Further, students also encounter chemical symbols, formulas, and equations which are used to represent both, the macroscopic and sub microscopic, levels symbolically (Scerri, 2006).

Thus, one of the main goals of chemistry education becomes assisting students navigate between representations. Indeed, Plass et al. (2012) contend that making sense of a range of such representations is the most important feature of learning chemistry as a practitioner. This manifests in chemistry teaching when educators try to provide rich learning environments that students can use to move between different representations to aid students' sensemaking. One way of delivering such environments is through the use of interactive computational simulations (Hunter et al., 2021). The use of such computer simulations as a tool in supporting students' sensemaking in various disciplines is a recent addition to the literature on the educational uses of interactive simulations (Haraldsrud & Odden, 2024). In chemistry, these simulations can provide interactive and visual representations of sub microscopic phenomena that are otherwise unobservable. By doing so, they provide students a way to make sense of dynamic theoretical entities that are hard to represent in textbooks but are crucial for understanding the way matter behaves (Plass et al., 2012). Simulations help students in inquiry learning by ensuring they are engaged in science process skills such as reasoning, hypothesis generation, observation and data interpretation (Kim & Hannafin, 2011). As a result, simulations may offer the affordances for students to engage in making sense scientifically through inquiry and problem solving (Plass et al., 2012).

Therefore, this research study explores the ways in which students use computer simulations to make sense of chemistry concepts while working to solve a problem in an inquiry-based lesson. By analysing student group work artifacts and through discourse analysis of student talk during the lesson, I describe how students engage in sensemaking through the use of a computer simulation as a tool. In addition, I aim to uncover the affordances of the computer simulations for sensemaking. In situating the study among teacher students, I also aim to understand the prospective teachers’ perceptions of using simulations in their own future chemistry teaching.

2 Background

This chapter presents a theoretical background on sensemaking and the use of simulations in science education to provide a review of relevant literature upon which the current study is based. In the first section, I give an overview on sensemaking as a concept in science education and, more particularly, within chemistry education. Next, in the second section I give an overview of the literature on the use of simulations in science education and in chemistry education. In the third section, I integrate the two concepts by reviewing the literature on the use of simulations as tool for sensemaking in science education. Next, I review a theoretical framework from literature on how to recognise sensemaking, which includes a method to capture sensemaking through analysis of student discussions. Finally, I include a section on the technology acceptance model (TAM) to review literature on technological change and its acceptance in education as I intend to use it to check if students' discussions are inhibited due to their aversion towards simulations as a new educational technology.

2.1 Sensemaking

The term sensemaking has been used in many fields to mean different but conceptually related practices that aim to make sense of something, of individuals and teams trying to create meaning of events and processes (Dervin & Naumer, 2017). Odden and Russ (2019a) enumerate such disparate fields such as artificial intelligence, organizational research, decision-making and science education. My use of this term in this research study is concerned about scientific sensemaking in the tradition of Ford (2012) and Kapon (2017) and the theoretical integration provided by Odden and Russ (2019a).

In trying to delineate the use of sensemaking in a science education context, I follow Odden and Russ (2019a) and other recent literature (Hunter et al., 2021; Haraldsrud & Odden, 2024; Andersen et al., 2024; Oh & Ha, 2025) based on it that addresses sensemaking. In this study, I do not study another approach towards sensemaking which is also emerging recently. This is the approach of blended sensemaking or sci-math sensemaking, which is described as the process of combining scientific knowledge and mathematical knowledge, which are separate cognitive resources, to generate a new blended understanding of mathematical equations used in science (Zhao & Schuchardt, 2021). Though this understanding of sensemaking is restricted to how mathematical equations are understood by students as part of science, recent literature has discussed how quantitative sensemaking of this kind is useful for science learning in general (Desi et al., 2026; Kaldaras & Wieman, 2023; Bowers et al., 2024).

It can be seen that even the strand of research stated above is complementary to research on scientific sensemaking as a whole and as such I have focussed mainly in following the lead of Odden and Russ (2019a). According to them, sensemaking is analytically different from other similar phenomena in education research, such as arguing, learning or explaining and this makes it important to define it more precisely. Their review of sensemaking literature brings to light three ways in which the concept has been dealt with in science education research.

Firstly, some literature has approached sensemaking from a cognitive perspective. In this tradition, researchers focus on the types of knowledge that are used by students to make sense of science. This area of research often seeks to understand how students gather, integrate, and use complex scientific concepts when they are making sense of scientific phenomenon. This strand of sensemaking leans heavily into conceptual change research in science education and thus, follow the two poles of contemporary conceptual change theories, which try to understand how students learn scientifically correct concepts: knowledge integration, and knowledge-in-pieces (KiP) (Odden & Russ, 2019a).

According to the knowledge integration framework, students integrate new knowledge into existing mental models through a process of comparison (Hunter et al., 2021). In the knowledge integration framework, students must restructure intuitive or naïve concepts they pick up from everyday life. Students come into scientific classrooms with theory-like knowledge structures which must undergo a process of change on the level of the whole theory for conceptual change to occur (Vosniadou, 2007). Within this framework, sensemaking is conceptualised as the comparison process, where a student integrates new facts and concepts of the scientific world within their existing mental model (Odden & Russ, 2019a). This integration is facilitated through student generated explanations called self-explanations, which is intra-subjective argumentation (Kapon, 2017).

In the knowledge-in-pieces framework knowledge is viewed as a complex system built out of many types of simpler knowledge elements by students integrating them into a system one by one. Here, learning involves selection from many old elements already known to students to form new configurations when faced with new knowledge resources (diSessa, 2018). This perspective posits that these resources connect to one another in particular configurations, which in different contexts, the students access to form ideas about how the world works (Odden & Russ, 2019a; Hunter et al., 2021). From this perspective, sensemaking becomes the process of resolving gaps or inconsistencies of the knowledge configuration in a particular context (Odden & Russ, 2019a). As noted by Odden and Russ (2019a), scientific models in chemistry can be represented in many ways and an important way in which students make sense of science is by coordinating multiple representations. Therefore, in the KiP framework, sensemaking can also be seen as extracting relevant features of multiple representations within one's knowledge configuration.

Secondly, as a discursive practice, sensemaking is seen in literature as a collaborative process involving ideas such as construction and critique from argumentation literature (Hunter et al., 2021; Ford, 2012). According to this perspective, when engaged in sensemaking, students are building an explanation by connecting pieces of evidence to back up a claim. This aspect, called construction, is similar to the connection process described in the cognitive perspective above. But in the discursive approach, researchers also analyse the process of evaluation that students engage in while building explanations, to make sure all the connected pieces are coherent with one another, called critique. Thus, from the discursive perspective, sensemaking is the process of building explanations through construction and critique. This can occur individually as intra-mental argumentation within oneself or collaboratively as an inter-mental argumentation among a group (Odden & Russ, 2019a).

Finally, another approach towards sensemaking is to think of it as an approach that students take towards science learning. In this perspective, researchers use the theoretical construct of framing to analyse sensemaking. Framing refers to the expectations that students bring to an activity, operationalised as the answer to the question “what's going on here?” (Odden & Russ, 2019a). Based on this research, students framing their activity as sensemaking see their task as building an explanation for a concept or phenomenon not understood using their own ideas and words (Hunter et al., 2021). Odden and Russ (2019a) compare other frames such as answer-making and memorising, which can also be frames taken up by students in science learning which are different from sensemaking. In an answer-making frame, the student wishes to find a formally correct answer or ask for one. This can be seen often in classrooms, where students go through courses but lack understanding of underlying principles. In this frame, students may default to strategies of manipulating formulae to quickly get to an answer without engaging with underlying physical mechanisms. The sensemaking frame represents an antithesis to such an answer-making frame, where students view their task as ascertainment of the mechanisms underlying phenomena (Odden & Russ, 2019a).

Taken together, the cognitive, discursive and framing approaches towards defining sensemaking reveal sensemaking to be a complex and inter-related set of processes that can be teased apart to distinguish sensemaking from other different but related theoretical constructs in science education. Odden and Russ (2019a) propose a definition of sensemaking that incorporates the various elements and approaches discussed above while being sufficiently distinct from similar concepts in science education such as learning, explaining, arguing and modelling. According to them,

> "...sensemaking is a dynamic process of building or revising an explanation in order to "figure something out"—to ascertain the mechanism underlying a phenomenon in order to resolve a gap or inconsistency in one's understanding. One builds this explanation out of a mix of everyday knowledge and formal knowledge by iteratively proposing and connecting up different ideas on the subject. One also simultaneously checks that those connections and ideas are coherent, both with one another and with other ideas in one's knowledge system."
> (Odden & Russ, 2019a, pp. 191-192)

They argue that sensemaking helps deeper learning, promotes transfer of learning across domains and initiates students into practices of science as followed by scientists. Thus, in a sense, sensemaking is the way in which students learn, by figuring something out using prior knowledge (Odden & Russ, 2018).

In chemistry, sensemaking is uniquely challenging because learning requires representational competence, that is, the ability to move between different levels of describing matter and processes affecting it (Moju et al., 2025). First conceptualized by Johnstone, researchers have identified three common levels at which chemistry principles and entities are represented. These are the macroscopic level (dealing with observable phenomena), the symbolic level (dealing with formulas and symbols), and the submicroscopic level (dealing with atoms and molecules) (Johnstone, 2009; Moju et al., 2025; Taber, 2013).

One issue that is persistent in chemistry learning is the fact that though these three different representations are all taught extensively in many years of schooling, they are often presented in isolation, without moving fluently between the forms which results in fragmentary learning

(Moju et al., 2025; Taber, 2013). Thus, there is a need in chemistry learning to foster sensemaking while addressing the discipline's unique demands. This has been operationalized by researchers as a need to connect the three levels of representations so that students can view chemistry as an interconnected system, where observable phenomenon are connected to symbolic representations and explained using submiscroscopic level entities like molecules and atoms (Moju et al., 2025; Taber, 2013). Taber (2013, 2015) explains the representational competence that is required for sensemaking in chemistry by giving us an example of a chemical reaction that a student observes (bubbling of the liquid medium). This reaction is contextualised as a chemical phenomenon through the use of symbols, formulas and a balanced chemical equation. Then finally, the student uses submicroscopic entities such as molecules and atoms to provide an explanation that describes the molecular basis of the reaction observed. Taber (2013) argues that in the context of chemistry, constructing explanations is an important feature of sensemaking, since it helps students to articulate their understanding of phenomena across representations, which is a hallmark of sensemaking in chemistry.

Drawing from these descriptions, we can construct a portrayal of sensemaking in chemistry as involving a complementary inter-relation of the three levels of chemical representations through the use of dialogue for describing phenomena, using symbolic representations and explaining through relevant submicroscopic models (Taber, 2013). Extending this idea of representational competence, Taber (2015) sees that the blending of knowledge of different subtopics within chemistry must also be integrated to understanding the sensemaking process in chemistry (Odden, 2021).

Using this definition of sensemaking in chemistry, we can review the literature to look at how sensemaking practices in chemistry learning can be supported. Russ and Odden (2017) suggest that practical or laboratory work can be a particular support because it makes students to go back and forth between reasoning using data and reasoning using models and thus presents an opportunity for developing representational competence. Pham and Tytler (2022) have suggested that using representations that combine both the observational level and the theoretical molecular level can be helpful in assisting student reasoning in this process by helping them deal successfully with the multistep nature of the reasoning process students must master across the different levels of representation. Thus, there is a need for moving across representations for aiding students' sensemaking in chemistry. Interactive simulations have been shown to enable students to visualize molecular interactions, while experimenting with quantitative and symbolic representations (Moju et al., 2025). This makes complex chemical processes more accessible to students and can be an aid in sensemaking practices (Moju et al., 2025). In the next section, I review the use of simulations in science education in general and further, particularly in chemistry.

2.2 Simulations in science education

Many studies have shown that interactive computer simulations enable students' conceptual understanding of science broadly and chemistry in particular (Smetana & Bell, 2012; Trundle & Bell, 2010; Zendler and Greiner, 2020). Plass et al. (2012) report that they found evidence that simulations enhanced students' learning of chemistry in the classroom. The authors of the study established that the use of simulations supported students' comprehension of ideas in chemistry and their ability to transfer their understanding to novel contexts. There are many ways in which such simulations are theorized to improve science learning of students. An important aspect of how computer simulations enable conceptual learning is the way it can help students visualize abstract concepts, manipulate variables and observe differing outcomes (Smetana & Bell, 2012). This helps students in making connections between real-world phenomena and theoretical understanding offered by textbooks (Kluge, 2019). Another aspect of simulations which help students conceptually is the visual nature of many simulations (Olympiou et al., 2013). An aspect of simulations which is crucial for their role in chemistry sensemaking is that they enable switching between multiple representations of molecules (Kozma & Russell, 2005). The dynamic nature of most interactive simulations is also offered as an explanation for learning gains realised through their use Trey & Khan, 2008).

There is diverse research on how interactive simulations influence learning in chemistry, across contexts and levels of education (Moore et al., 2014). Specifically, modelling competence, which is deemed to be important for sensemaking in chemistry, was shown to be supported in undergraduate students through the use of computer simulations (Clark & Chamberlain, 2014; Haraldsrud & Odden, 2024). Another study by Salame and Makki (2021), in a similar college level course shows that using impacted positive affect while also improving learning. Affective aspects of learning such as motivation was seen to be increased along with confidence in students using a simulator of electronic circuits (Ronen & Eliahu, 2000). Studies focussed on learning perceptions and conceptual learning in secondary school students focussing on the use of interactive simulation tools like PhET demonstrated benefits in wide ranging topics like particulate nature of gas and chemical equilibrium (Correia et al., 2019; Ganasen & Shamuganathan, 2017). Further, a recent systematic review of studies on PhET interactive simulations into the teaching and learning of chemical concepts by Aliyu et al. (2024) found that across high school and college level chemistry a variety of concepts such as physical chemistry, chemical bonding, states of matter, chemical equilibrium, and acid-base chemistry have been taught through simulations.

Along with conceptual learning research, research on simulations in chemistry has included studies on students' development of science process skills from very early on (Faryniarz & Lockwood, 1992). Recent studies have also shown that students using computer simulations learn science process skills at a rate comparable or better than those using traditional methods (Beichumila et al., 2022; Celik, 2022). Haraldsrud and Odden (2024) propose that the mistake friendly environment provided by simulations, where students are allowed to make errors and learn from them may encourage students to take risks in their learning, which might foster the development of their science process skills.

The discussion above on the effectiveness of computer simulations has to be tempered with some considerations from the systematic review conducted by Smetana and Bell (2012). In their review, Smetana and Bell define some key pedagogical factors that are relevant to the effectiveness of simulations. A major factor, they found, is the use of simulations in addition to traditional methods instead of using simulations to replace those methods. Similar findings from a large meta-analysis on the effects of guidance on inquiry learning by Lazonder & Harmsen (2016) also points out the effectiveness of traditional learning based on the lecture method is not replaced by inquiry learning, whether through simulation use or not. Thus, the context of simulation use is important for supporting students in chemistry learning and more so for aiding in sensemaking, since students can learn about scientific phenomena without integrating them or making sense of the new learning (Odden & Russ, 2019a).

Inquiry learning, in particular, has been an area of study regarding use of simulations and other digital technologies. Computer-Based science inquiry learning environments, which included simulations, were reviewed by Donnelly et al. (2014). The authors found that such environments helped students learn in authentic contexts while developing metacognitive practices and collaboration. In his article reviewing engaged learning in STEM, de Jong concludes that inquiry led use of simulations fared better than direct forms of instruction for acquiring conceptual knowledge (De Jong, 2019). He reports positive results in such digital environments for student interest in science as well. In his review, de Jong also posits some advantages of virtual labs and simulations over traditional laboratory settings. According to him, the use of such digital technologies offers practical advantages, such as unhindered lab availability and access to data (De Jong, 2019). He also allows the possibility that technology can be used to integrate guidance in inquiry learning in an adaptive manner (De Jong, 2019). In the next section, I delineate the research on sensemaking in science using simulations as a pedagogical tool.

2.3 Sensemaking and computer simulations

Multiple recent studies have shown that simulations can aid sensemaking in science. Haraldsrud and Odden (2024) suggest ways in which processes like modelling and science process skills relate to sensemaking. According to them, sensemaking shares a relationship with modelling and science process skills as they relate to scientific inquiry and they involve students engaging actively to apply scientific concepts and principles. When we focus on sensemaking we are emphasising certain features of these processes while de-emphasising certain others. For example, while science process skills emphasise the methodology of science, sensemaking focuses on the why of science (Haraldsrud & Odden, 2024). Similarly, while sensemaking may involve modelling there is an emphasis on the integration and interpretation of meaning from these models rather than the construction of models, which is where the focus of modelling lies (Haraldsrud & Odden, 2024; Sands, 2021).

Petter Sand et al. (2019) argue that the students could engage in sensemaking because the computational activity allowed them to realize inconsistencies in their knowledge frameworks and to easily construct explanations to bridge their gaps in understanding. While reviewing this article, Haraldsrud and Odden (2024) also claim that the approach used by the students allowed them to work actively with models, while continuously testing them. The notion that computer simulation aids model-based thinking which in turn can contribute to sensemaking has been studied by Sands (2021). According to Sands, modelling and sensemaking share similar attributes: the construction and critique of explanations of real-world phenomenon. He also discusses how the modelling process moves between critique and building an explanation, which is an essential element of sensemaking (Sands, 2021). Modelling and science process skills also share some features with each other. Kluge (2019) shows that simulations can be used as a connection between theory and previous experience. It is seen from literature that computational simulations used along with traditional lab work can enhance conceptual understanding and science process skills better than regular lab activity alone (Celik, 2022). Thus, it seems that simulations can offer some affordances for sensemaking that are not present in regular lab work (Zendler & Greiner, 2020).

I follow Haraldsrud and Odden (2024), in their reasoning about how interactive simulations may facilitate sensemaking. Haraldsrud and Odden (2024) show that simulations provide a basis for evidence in claims during students' discussions about chemistry concepts. Interactions between the simulation, theory and self-generated explanations also provide meaning and thus, promote the process of sensemaking in the students. As argued by Hunter et al. (2021), Haraldsrud and Odden (2024) also value the dynamic representations produced by simulations which can give students an understanding of fundamental concepts in chemistry. They also discuss the ways in which simulations may bridge the gap between macro-level observations and micro-level explanations, by letting students explore the micro-level while observing corresponding changes at the macro-level.

Based on their study and previous literature, Haraldsrud and Odden (2024) propose four key affordances of simulations for sustaining sensemaking in students. Affordances refer to the properties of technologies that determine their possible utility and usability (Lainema et al., 2023).The concept of affordance has been used in multiple ways in various fields such as education, technology and media studies (Lainema et al., 2023). According to Berthelsen and Tannert (2020) in education, technological objects, such as digital learning materials, have affordances that designers must use effectively to provide learners, with engaging learning opportunities. As described by Haraldsrud and Odden (2024), the affordances provided for simulations to sustain sensemaking are characterised as, the explorative factor, the feedback factor, the representational factor and the uncertainty factor. In the next sections, I explore each of these factors through the literature to try to tease out the elements in simulations that facilitate sensemaking.

Exploration

In their study, Haraldsrud and Odden (2024) highlight the importance of exploration when using simulations as a tool for learning. According to them, a computational simulation affords exploration because of its interactive element that encourages students to study the effect of variables. As pointed out by de Jong et al. (2023), computer simulations often go hand in hand with the predict-observe-explain cycle of inquiry learning. This provides the opportunity for students to play around with a list of parameters that correspond to variables in the simulation, while also making it possible for students to visualise the outcome of such interactions between variables (Dalgarno et al., 2014).

In their study, Dalgarno et al. (2014) noted that students who explored the simulation systematically outperformed students who did not have the opportunity to set simulation parameters themselves. They explain this by interpreting their results with a constructivist lens. According to them students afforded the opportunity to explore the simulation had better support in the iterative construction of knowledge. This iterative construction is similar to the sensemaking view as delineated by Kapon (2017). Thus, simulations may help sustain sensemaking through affording systematic exploration. Podolefsky et al. (2010) argue that exploration through simulations can lead to sensemaking only if there is guidance through scaffolding built into the tools. The authors also claim that simulations are useful when students readily perceive that they can take certain actions and make sense of the phenomena when exploring the simulation. This can be done, for example, by using concrete objects as hooks for engaged exploration and sense making. Another reason for why students can sustain sensemaking using the explorative potential of simulation is the fact that students tend to explore simulations in ways that are intuitive for them (Podolefsky et al., 2010). The authors argue that this freedom to explore along their own path is important for inquiry and sensemaking since it emulates aspects of scientific practice.

While exploration is an important factor, Odden and Russ (2019a) insist that students can be nudged towards sensemaking only after the students have already encountered the concepts beforehand. Odden and Russ (2018) emphasize that students must engage in a certain amount of metacognitive reflection to pin down and articulate their gaps or inconsistencies in knowledge, which is an entry condition to sensemaking. Thus, affordances other than just exploration are also important for why simulations can sustain sensemaking.

Feedback

In their study on interactive simulations, Moore et al. (2013) observes that computer simulations are designed to ensure that interactions are intuitive and often result in productive

feedback for sense making. This is similar to the finding of Haraldsrud and Odden (2024), that immediate feedback can serve to keep students engaged in a task for a longer amount of time, which is crucial for sensemaking to emerge as opposed to answer-making. They continue by arguing that tools that allow students to become aware of their own errors through immediate feedback can be resources for sustaining sensemaking in chemistry. In their study on scaffolding using computer simulations, Kaldaras et al. (2024) suggest that feedback is essential for supporting a learner to construct further upon existing knowledge, in a manner similar to Kapon's (2017) understanding of sensemaking. They also assert that simulations provide an environment suitable for supporting sensemaking with its embedded feedback. They also identify immediate feedback as one of the features of simulation design that support problem solving and sensemaking among students (Kaldaras et al., 2024).
In their study on student errors Metcalfe and Kornell (2007) reported that student performance was better on concepts where they were given feedback after initial wrong notions were identified. They suggest that feedback was the most influential factor in correcting persistent wrong notions of students. Haraldsrud and Odden (2024) also discuss reasons why feedback is important as an affordance for sensemaking. They argue that students use simulations essentially as feedback loops, where they test their ideas repeatedly and this testability increases confidence in their own reasoning, leading to sustained sensemaking. Thus, simulations by virtue of being used repeatedly and providing immediate output, encourages hypothesis testing, which can lead to sustained sensemaking in students.

Representation

Podolefsky et al. (2010) argue that exploration as an affordance is useful essentially because simulations can show representations of phenomena that are ordinarily not possible for students to see. They propose that simulations also provide representational resources in the form of analogies that serve as basis for students to make sense of new ideas. This is similar to the idea of conceptual blends from Odden (2021). Odden suggests that analogies create connections between different domains to make meaning. He concludes that such blending between different conceptual domains provides resources for sensemaking.

For Haraldsrud and Odden (2024), the important representational affordance for simulation is the movement between different levels of representation, between micro to macro to symbolic which is possible for students themselves to move through. According to Hunter et al. (2021), many studies show that dynamic representations in chemistry improve students conceptual understanding. Sensemaking in chemistry especially relies on student ability to coordinate multiple representations (Sirnoorkar et al., 2023). According to Rau (2018), sensemaking correlates to students' ability to identify differences and similarities between multiple representations in chemistry. Thus, simulations, with their ability to help students move between multiple representations, provide resources to students to make sense of such representations by helping them identify these differences and similarities quickly.

Uncertainty

Haraldsrud and Odden (2024) posit that simulations can provide students results that contradict their previous experience. According to them, this creates the sense of uncertainty for students, which can help students prolong the sensemaking process. In their study, the simulation output often conflicted with the students' prior knowledge. This made it necessary for students to engage in repeated discussion to try resolve this contradiction. This uncertainty was a key difference between sensemaking and answer-making as answer-making requires certainty of the correct answer, which is denied by the uncertainty created by the simulation.

Previous research on student uncertainty corroborates the view discussed above. Ha, Park et al. (2024) discuss how student scientific uncertainty has been shown to afford students the space for students to evaluate their understanding of scientific phenomena while discussing their gap in knowledge. This evaluation helps them sustain the cognitive demand required in sensemaking since it makes them engage in productive struggle (Ha, Park, et al., 2024). Ha, Park et al. (2024) found that students' scientific uncertainty can be a potential resource to develop the sensemaking. According to their study, Conrath et al. (2025), state that uncertainty in the digital curriculum created opportunities for students to participate in argumentation while making sense and negotiating with other students. By enabling students to carefully work through this uncertainty, as opposed to quickly resolving the uncertainty, digital tools like simulations, can offer students resources for sensemaking (Conrath et al., 2025). Indeed, this was seen clearly in a study by May et al. (2022) where the authors found that students engaged in sensemaking by debating competing hypotheses, while critiquing available evidence and constructing scientific explanations. They also found that students resolved inconsistencies by testing a series of experimental procedures (May et al., 2022). As we have seen before, simulations help students in testing hypotheses repeatedly. By helping students test their ideas repeatedly, simulations can also help students navigate uncertainty while engaging in sensemaking to resolve inconsistencies, whether within their prior knowledge or from results produced by the simulations themselves.

2.4 Capturing and recognising sensemaking

While deliberating on defining the characteristics of sensemaking, Odden and Russ (2018) present the epistemic games framework as a means of showing the trajectory of a sensemaking episode. They propose that using the epistemic games framework is particularly useful since it would help educators and researchers gain a holistic perspective on the process than just studying the characteristic hallmarks of the process would. In their study, they use the case they deal with to inductively arrive at certain parts of the process of sensemaking through paying close attention to the starting point, the ending point and what happens in between (Odden & Russ, 2018). In the current research study, I have used the theoretical framework of epistemic games to identify how sensemaking happens in student discussions.

2.4.1 Epistemic Games

Epistemic games framework has been commonly used in science education research to describe how students approach tasks like solving a problem. The framework uses the features of games, such as rules, moves, beginning point and ending points to address the processes of inquiry. In this regard, epistemic games have certain key features to differentiate between different epistemic games. According to Odden and Russ (2018), each epistemic game has a unique epistemic form. This target epistemic form is the form of knowledge that the game is supposed to produce and if produced, the game is completed successfully. For example, if the game is the answer-making game, the target epistemic form is the correct answer to a question. Students playing the answer-making game endeavour to complete the game by getting to this right answer. Odden and Russ further elaborate this form by discussing the notion of constraints within the epistemic form. In the answer-making game, for example, there might be constraints in the fact that there can be only one correct answer, or that the answer has to be expressed in a compact form as opposed to a long essay. Thus, taken together, the epistemic form and constraints define the rules or the parameters of a particular epistemic game (Odden & Russ, 2018).

Refining the original idea from Collins and Ferguson (1993), Odden and Russ posit that an epistemic game is also characterised by the entry conditions, the moves within the game and an exit condition or a resolution. They further link the epistemic games framework to their theoretical description of sensemaking to generate a set of conditions and parameters that characterise the trajectory involved in student sensemaking. According to them, the entry condition specifies what constitutes the beginning of an epistemic game. In their study, Odden and Russ (2018) find that the first articulation of a gap or inconsistency in knowledge acts as the entry condition into the sensemaking game. In all of their analysed examples, there is a shifting from other games into a sensemaking game only when there is an articulation of the inconsistency in their understanding of a phenomenon. Hunter et al. (2021) further refine the notion of an entry condition by noting that the questions of the activity in their study were often gaps in understanding that students then tried to resolve. Thus, students vocalizing the questions from their activity sheet served as an entry condition for sensemaking.

Moving on to epistemic form, Odden and Russ (2018) propose that generating an explanation that resolves the inconsistency articulated in the entry condition is the goal or the target epistemic form for the sensemaking epistemic game. The authors generate some rules, or constraints, for an episode to consist of the sensemaking epistemic form. These rules include the fact that it there is a two-way discussion between students around a topic or idea that one has not already made sense of yet. The discussion should also include students' own ideas and not just appeals to authority, where the ideas are bounced off each other to make new conceptual connections used to construct understanding (Odden and Russ, 2018). Hunter et al. (2021) and Haraldsrud and Odden (2024) add to this list the notions of real-world framing, robust explanation building and quality of explanations which distinguish the epistemic form of the sensemaking epistemic game from other epistemic games like answer-making.

According to them, during sensemaking, students use their previous experiences from the real world as cognitive resources. Real-world phenomena allow students to make connections from their experiences to the scientific explanation they are trying to construct. Odden and Russ (2018) also notice similar moves in the epistemic games of the students in their study. There, students involved in sensemaking appealed to past experience, appealed to common sense knowledge and built analogies in order to advance their explanations. Hunter et al. (2021) further suggest that robust explanation building involves student discussions that build and critique each other's ideas. Haraldsrud and Odden (2024) also note that this process of building explanations often involves vexing questions that guide the explanation building. Ford's (2012) account of sensemaking as argumentation addressed this issue of vexing questions. According to Ford, such vexing questions initiate and sustain the sensemaking process by creating a discomfort that motivates students to continue building their explanations until the inconsistency is resolved instead of giving up in the face of uncertainty or appealing to authority, both of which can mark an exit from sensemaking. Indeed, Ford argues, sensemaking necessarily involves an oppositional voice, where students not only construct sense but also seek to critique it while identifying potential errors in their reasoning. Vexing questions form an essential part of such dialogue that sustains sensemaking.

This element of question asking was further elaborated by Odden and Russ (2019b). They conjecture that questions serve a critical role in initiating the sensemaking process. In their study, they identified that vexing questions help stabilize the sensemaking process. Their analysis suggests that when students have found a sufficiently vexing question, they may be more inclined to stay in the sensemaking game and head off potential endpoints for their discussions. According to them, the questions worked to sustain sensemaking because the students were frustrated by the underlying gaps or inconsistencies in knowledge and were driven to resolve them, similar to the drive mentioned by Ford (2012).

Finally, Hunter et al. (2021) and Haraldsrud and Odden (2024) add quality of explanation, in their list of evidence for the sensemaking epistemic game. In the context of their studies, they evaluated the quality of explanations based on based on completeness of students' written work using the scientific explanations framework in terms of claim, evidence and reasoning. The authors build on the work of McNeill et al. (2006 as cited in Hunter et al., 2021). According to McNeill et al., scientific explanations in science classrooms involve students trying to explain how or why a scientific phenomenon occurs. Within this framework, an explanation contains of a claim which is supported by evidence. Finally, there must be explicit reasoning that connects the claim to the evidence in order for the whole explanation to be judged as a scientific explanation. The presence of such complete scientific explanations can be taken as a means of inferring the sensemaking epistemic form as opposed to an answer-making form (Hunter et al., 2021).

The last characteristic of an epistemic game is the exit condition or the resolution. According to Odden and Russ (2018), the resolution is the product of the form, and either is successful if the epistemic form is reached or unsuccessful if the game transfers or moves out into other games. In the case of the sensemaking game, the resolution is either the constructed explanation of the inconsistency that fills the gap in knowledge or moves into other forms such as asking authority or answer-making or accommodation of the inconsistency within existing knowledge constructs. Haraldsrud and Odden operationalise the resolution as the "explicit voicing of a conclusion to the entry condition, backed up by previous arguments." (2024, pp. 766). Hunter et al. (2021) use a similar definition with the addition that the resolution must be a "Confident response not posed as a question or with hedging language" (2021, pp. 334). Odden and Russ (2018) articulate that it is difficult to predict what helps students reach a resolution in their sensemaking game and the lack of pattern made it difficult to anticipate what might help students successfully resolve an episode as opposed to quitting or moving to a different game. They spend considerable effort in establishing that the movement to and from sensemaking can be usefully analysed through the concept of framing.

Framing refers to how anyone answers the question "what's going on here?" (Odden & Russ, 2019a). According to them, people view their activity by interpreting experiences in previous, similar activities, which results in creation of frames that are used for responding to different situations. With respect to learning, these have also been called epistemological frames. In a sensemaking frame, students view their prior experiences, interests, and identities as important resources for contributing to the figuring out taking place in the science classroom. This frame involves students calling upon everyday experiences as important sources of knowledge for making sense of the problem at hand (Odden & Russ, 2018). One finding from the literature on sensemaking and framing is that students tend to shift in and out of sensemaking frame as it is unstable. Students will move among frames, especially within a group where individual's frames may interfere with one another (Hunter et al., 2021). The shifts can be moment-to-moment or very minute (Odden & Russ, 2018). This suggests that students may only be sensemaking for a short time before they shift to other frames or approaches to science learning. Therefore, any analysis of the sensemaking epistemic game must necessarily look at the structural components of the epistemic game, along with the moves made by the students in a sustained manner to argue for the existence of sensemaking.

2.4.2 Mechanistic Reasoning in sensemaking

The presence of complete scientific explanations is important in inferring the sensemaking epistemic form (Hunter et al., 2021). Previous studies in sensemaking make use of McNeill's framework for understanding quality of explanations to infer sensemaking epistemic form (Hunter et al., 2021). Recent research on sensemaking has included mechanistic reasoning as an important characteristic for sensemaking since many phenomenon in science have an underlying mechanism which may not be visible or may not be brought to attention of students at first (Gili et al., 2025). It has been noted that reasoning about mechanisms is one of the most important aspects of inquiry in science (Bolger et al., 2012). According to the literature, mechanistic reasoning in science focuses on the cause–effect relationships between constituent components of a system, where the student actively thinks about how changes in components affect one another (Russ et al., 2008; Russ & Odden, 2017). Thus, this research study also looked into the characteristics of mechanistic reasoning as developed by Russ et al. (2008). An account of mechanistic reasoning considers not only a description of some phenomenon but also provides a theoretical reasoning behind the empirical observations due to this phenomenon. That is, reasoning mechanistically involves proposing and reasoning through potential mechanisms through which the phenomenon presents itself (Krist et al., 2019).

To study student thinking through the lens of mechanistic reasoning, Russ et al. (2008) developed a coding scheme through the discourse analysis framework of previous researchers working in the field of scientists' mechanistic reasoning. According to the authors, the coding scheme can be arranged hierarchically, with the quality of evidence for mechanistic reasoning becoming better with the presence of higher level codes (Russ et al., 2008). Any code, if present in any of the discourse being analysed, marks evidence of mechanistic reasoning. Also, more codes in any piece of discourse also indicates more compelling evidence for the presence of mechanistic reasoning (Russ et al., 2008). While analysing a piece of discourse, the authors urge caution with interpretation, suggesting that the coding scheme is a means of tabulating evidence for mechanistic reasoning, while asserting that there is no threshold for concluding that students are using mechanistic reasoning (Russ et al., 2008). They also make it clear that the hierarchy does not indicate development sequence and thus, this coding scheme is not meant to be a pedagogical rubric. This coding scheme had a high interrater reliability and thus can be seen as a reliable tool for analysing student discourse in science (Russ et al., 2008).

2.5 Technology Acceptance Model (TAM)

The use of technology in education is often mediated through the experiences of the teacher (Estriegana et al., 2019; Ursavaş, 2022). Even though inclusion of technology in instruction is seen as a key idea in many education reform agendas, just the introduction of new technologies by themselves do not guarantee an increase in students' success (Ursavaş, 2022). This might be because teachers might have difficulties in integrating technology within a pedagogically relevant lesson in various degrees (Ursavaş, 2022). Theoretically, the

Technology Acceptance Model (TAM) has been developed and used by researchers to gauge the perceptions of technology users. TAM surveys often includes the usability of a technology, attitudes and behavioural beliefs of users towards that technology (Ursavaş, 2022). TAM has been used by researchers in various ways. According to literature, it has been used in healthcare, finance, organisations and household use (Estriegana et al., 2019). However, the TAM has also been used extensively to study acceptance of technology in education, by both teachers as well as students.

The TAM is an information systems theory that models how users accept and use technology. It was developed by F.D. Davis in 1989 while understanding reasons why users accept or reject certain information systems (Ursavaş, 2022). According to Davis, two important personal beliefs, the Perceived Ease of Use (PEU) and Perceived Usefulness (PU) shape the behavioural intention to use a particular technology. Perceived usefulness is defined by Davis as the perception of the usefulness of a technology to do a certain job. For example, if a teacher sees the benefit of using interactive simulations in their classes, it means that the teacher has a higher PU and may have a positive attitude toward using simulations in their classroom instruction. Perceived ease of use refers to the perception the technology does not require additional effort to use effectively. Both PU and PEU affect users differently, according to their experience and expertise. For example, inexperienced users may focus on the ease of use when faces with a new technology, while more experienced users may focus on the usefulness of that technology to their jobs (Ursavaş, 2022). The use of TAM to understand technology use in education is underpinned by the realisation that the best technology available is useless if students and teachers are not interested and able to use them. The use of computer simulations for science learning has not been studied extensively using the TAM framework. This study used TAM surveys to understand the participants' perception of simulations as both a learning as well as a teaching tool.

3 Methods

This chapter provides a systematic description of how the study was organized and conducted. It generally focuses on the presentation of the research design consisting of the research setting including the sample, the instruments employed in the study as well as details about what data was collected, how it was collected and how it was analysed.

3.1 Research Questions

This study aims to investigate the dynamics of sensemaking in an authentic chemistry learning environment mediated using interactive computer simulations. It is guided by two the following research questions:

Research Question 1: How does sensemaking happen in a university chemistry class while using computer simulations as a pedagogical tool in an inquiry-oriented lesson?

Research Question 2: What are the affordances offered by the computer simulations that promote sensemaking in a university chemistry class?

These questions seek to uncover the processes involved in student sensemaking using interactive computer simulations in an inquiry-based lesson in chemistry. This was done by describing how students discuss and work to solve real-world based problems through interactions with computer simulations while analysing the affordances simulations offered the students in this sensemaking process.

3.2 Research Design

3.2.1 Setting

The setting for this study consisted of 13 chemistry teacher students enrolled in a 3rd-year university course on inquiry-based lab teaching. The medium of instruction for the course was Finnish. In this course each week students attended a three-hour session which generally was setup as an inquiry lab. There was a pre-work before every session, with the students expected to learn some concepts relevant to the course, tested through a quiz. In the session, the students were introduced to an open or guided inquiry task, which was explained by the instructor, typically in the first half hour. The students then conducted their inquiry and drafted a report answering the questions in the task in the next hour. After a break, the students re-assembled and the instructor debriefed the students along with time for discussion and time for reflection.

This specific population was chosen as a convenience sample because the instructor of the course was interested in sensemaking research and helped with the setup and gave time to the researcher to conduct the activity described below. Further, since the students in the sample were becoming teachers, this research might be useful to their future teaching practice. Most participants (11 out of 13) were chemistry majors, while the others were taking chemistry as a minor subject. For everyone in the group, this activity represented their first interaction with simulation-based teaching. Most of the students had seen computer simulations and a few had used them in their studies, but none of them had used it in their previous teaching practice. This sample provided a unique perspective for this study, since these students were also evaluating the simulations as pedagogical tools they may eventually use in their own classrooms. Consent forms and privacy notices (Appendices 1 and 2) were given to the students in the session in the previous week before the research took place. Students were informed prior to their consent that participation had no impact on their course grade and that they could withdraw their consent at any point in the study.

3.2.2 Designing the simulation based activity

The activity was designed following the POGIL based activity from Hunter et al. (2021). Similar to their activity, the activity in this research study utilised an interactive molecular dynamics simulation developed by the Concord Consortium that models gas behaviour (https://mw2.concord.org/public/student/gaslaws/index.html). The simulation provided a visual, particulate-level representation of gases within a piston system. The simulation allowed students to manipulate six independent variables: temperature, pressure, number of particles, particle mass, particle size, and particle attraction in two side by sides containers, so that the effect of the variables could be studied without a need for quantification, through the comparison process. The simulation operated as a virtual experiment environment where students could change variables and observe real-time outcomes. For example, increasing the particle size variable immediately alters the visual appearance of the particles and the resulting pressure or volume of the system, allowing students to visualize abstract concepts that are otherwise invisible. The simulation was designed to bridge the gap between microscopic molecular interactions and macroscopic observations. A sample screenshot from the simulation is added below in Figure 1.

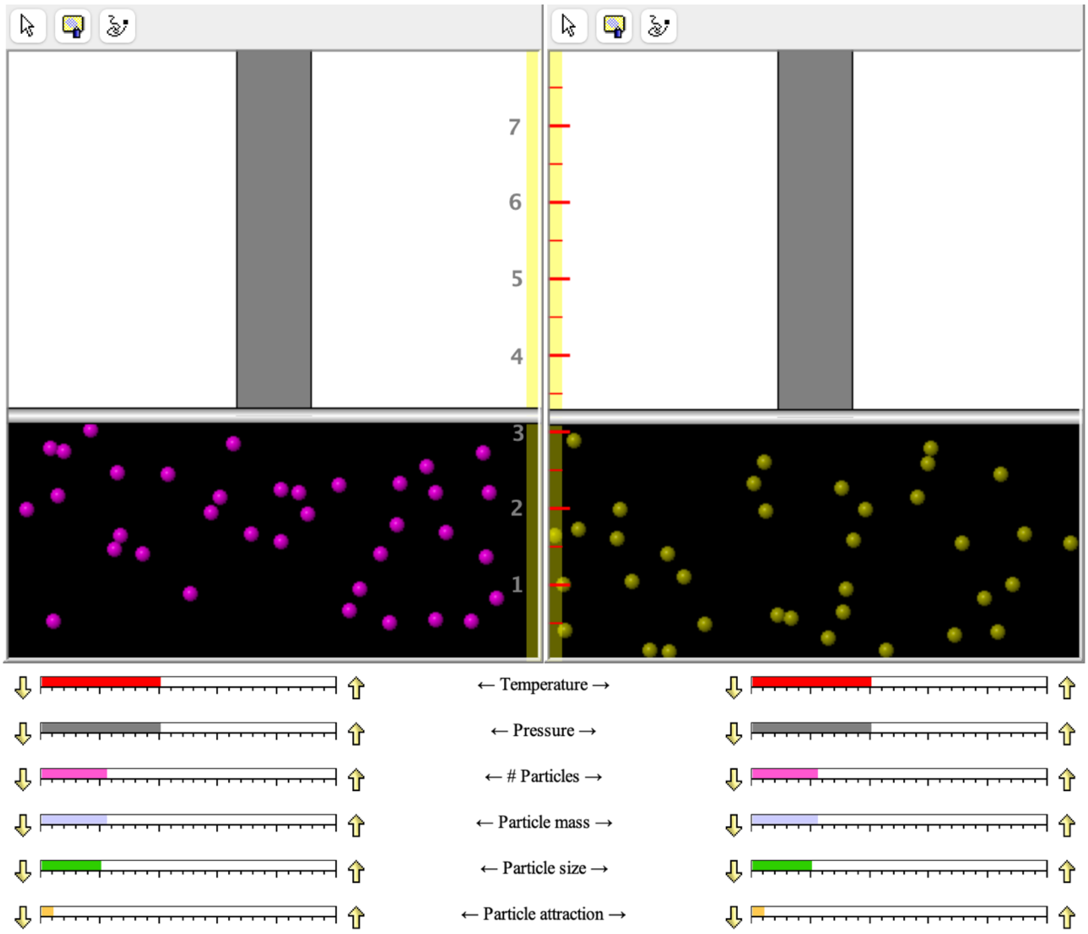

Figure 1. Screenshot of the interactive simulation of gas laws developed by the Concord Consortium

The activity was designed around a core problem adapted from a problem written by Izzar Linares from the Chemistry Problem-Based Learning (PBL) site hosted by the University of Toronto Mississauga (UTM) (*Road to the Red Planet | Problem-Based Learning*, n.d.). The activity was designed as a worksheet which focussed on getting students familiarised with the simulation. The worksheet was designed taking into account research by Veermans and Jaakkola (2019) which provided the template for the characteristic pedagogical flow by offering scaffolding for the students to predict, investigate and infer concepts. The questions in the worksheet focused on conceptual understanding rather than procedural problem solving. The worksheet was initially written in English and then translated by the instructor of the course to Finnish. The students were provided with both the English and the Finnish versions of the worksheets during the session.

The worksheet was problem-based, utilizing a context of evaluating the structural integrity of a proposed oxygen storage system for use in Mars against manufacturer's claims. Students were tasked with validating a manufacturer's claim that a storage tank was safe for Mars' extreme temperature ranges. This context was chosen because it represented a real-world problem, which was engaging to the students and allowed students to draw on their prior knowledge and personal experiences (e.g., winter conditions, gas laws) to make sense of the problem. The activity sheet explicitly prompted students to explain their reasoning in full detail, so that the students may write detailed explanations along with reasoning, which might stimulate sensemaking (Russ & Odden, 2017). The worksheet was designed to maximise opportunities for working with the simulation, while providing opportunities of sensemaking to the students.

In the first phase of the activity, students were familiarised with the simulation by means of exploring the effect of the number of particles, temperature, and pressure on the volume of an ideal gas. This initial phase also familiarises them with the predict-observe-explain cycle used in POGIL tasks and other inquiry learning tasks. This is done by asking the students to hypothesise what the relationships would be before they can test it in the simulation. This design follows closely from Veermans and Jaakkola's (2019) research studies on simulations. Next, the students apply their understanding of gas laws, along with exploration of the simulation to answer the core problem of whether the storage system would withstand the temperature extremities of Mars. To ensure that students discuss the phenomena and scientific principles, rather than just answer a numerical problem by algorithmically solving an equation, the question was open ended as the material of use, the actual pressure the tank could sustain, the amount of oxygen etc. was left out of the problem. This made the students think about what could be solved using the simulation, what has to be assumed about the tank and the principles behind the gas laws. In the second part of the worksheet, students had to focus on the variables not included in the ideal gas law: particle mass, particle size, and particle attraction. The students predicted the effect of these variables under certain conditions and predicted the influence the variables may have on the ideal gas law equation under different conditions. In the final part of the worksheet, students were prompted discuss the relationship between a real and an ideal gas while solving a real-life problem. The complete worksheet is included in the Appendix 3.

The worksheet was based on inquiry learning since the course in which the activity took place was an inquiry-based laboratory teaching course. Also, inquiry learning has been at the forefront of science learning and is especially relevant to sensemaking (Ford, 2012). Inquiry-based learning (IBL) is defined as an educational strategy in which students follow methods and practices similar to those of professional scientists to construct knowledge. At its core, it is a process of discovering new causal relations, where learners formulate hypotheses and test them by conducting experiments or making observations (Pedaste et al., 2015). Unlike traditional instruction, which often focuses on the transmission of established facts, inquiry-based learning emphasises active participation and self-directed exploration. In higher education, this approach is seen as important for building a scientifically literate community (Pedaste et al., 2015).

3.3 Data Collection

Primary data was collected from many sources, including surveys, student written work and transcripts from the video recordings from the sessions. This section details the different kinds of data collected in this study along with some comments on the purpose of such data collection.

3.3.1 Data from TAM Surveys

To evaluate the participants' perceptions of the use of simulations in science learning, a set of Technology Acceptance Model (TAM) surveys were administered, one before the activity and two after the activity. The survey included 10 items scored on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree). These items measured three core constructs: perceived usefulness (e.g., "Using the simulation helped me develop a deeper understanding"), perceived ease of use (e.g., "I found the simulation easy to use"), and intent to use the technology in future teaching. The TAM is a validated tool for predicting a user's willingness to adapt to new technology based on whether it is perceived as uncomplicated and beneficial to learning (Silva, 2015). This present study used TAM surveys adapted from Musa et al. (2023). The pre-activity survey included questions on students' perception on own learning using simulations before the activity (Pre-session Questionnaire in Appendix 4). The post-activity questionnaires included one TAM survey on the perceptions on own learning using simulations after the activity (Post-session Learning Questionnaire in Appendix 5) and one TAM survey on the perceptions of teaching using simulations (Post-session Teaching Questionnaire in Appendix 6). Another survey was conducted post task to determine how authentic the simulation was in stimulating sensemaking in real classroom contexts (Post-session Sensemaking questionnaire in Appendix 7). This survey was modified from a similar instrument from Musa et al. (2023), which focussed on the authenticity of the virtual patient simulation used in their study.

3.3.2 Data from simulation activity session

The primary data from the student discussion were collected during a three-hour session where the participants in the study worked on the worksheet activity described in the previous section. In the session, students worked in small groups (two pairs and three groups of three) to encourage collaborative discussion to induce sensemaking. On the day of the session, the instructor introduced me and the aim of the research, once again stressing them to articulate reasons loudly while working through the activity. The students were split into two groups of two and three groups of three for a total of five groups. Each group had one laptop with the simulation loaded and ready to be used. A screen recording, video recording and audio recording software (OBS) was started as soon as the students were handed the activity worksheet. The students were also clearly told that they could discuss in any language of their choice.

Data collected from this session included:

1) Worksheet Activity Sheets: Students provided written explanations, completed questions, and created particulate-level sketches according to different task instructions.

2) Video and Audio Recordings: Group discussions were recorded in situ to capture authentic peer interactions without researcher intervention. The video was transcribed using transcription software from EU. The resulting transcript was then translated into English from Finnish for analysis. This translation was also done using EU digital tools.

3.4 Data Analysis

This section details the analysis of the different kinds of data collected as described in the previous section. This section also highlights the coding scheme used in the qualitative analysis of the data

3.4.1 Quantitative analysis of TAM surveys

The TAM survey data were analysed using descriptive statistics. Analysis focused on mean scores for all of the 10 items to determine overall technology acceptance as well as means for each construct, perceived usefulness, perceived ease of use and perceived interest. Means were calculated and used to evaluate differences in perceptions between the pre and post activity learning questionnaire as well as post task learning versus teaching questionnaire comparing how teacher students perceived the simulation's benefit to their own learning versus its benefit for their future students.

3.4.2 Qualitative analysis of activity worksheet

Student writing from the activity worksheets were analysed through two lenses. First, the written answers were analysed for the presence of mechanistic reasoning by coding the answers using Russ et al.'s (2008) coding scheme. The coding scheme is given in Table 1.

Table 1. Coding scheme for identifying mechanistic reasoning, from Russ et al. (2008)

Code	**Code Description**
Describing Target Phenomenon	Students state or demonstrate the particular phenomenon or result they are trying to explain
Identifying Setup Conditions	Students identify particular enabling conditions of the environment
Identifying Entities	Students articulate objects that affect the outcome of the phenomenon
Identifying Activities	Students articulate actions and interactions that occur among the entities
Identifying Properties of Entities	Students articulate general features of entities that are necessary
Identifying Organisation of Entities	Students describe or model where entities are located spatially and how they are organized
Chaining: Backward and Forward	Students use knowledge about the causal structure of the world to make claims about what must have happened previously or what will happen next
Analogies	students compare the target phenomenon to another to reason about the target phenomenon

This analysis helped in identifying if students were using mechanistic reasoning, which was used as evidence for sensemaking in the discussions based around those questions. Second, a thematic analysis was done on answers which identified student perceptions of simulation affordances on questions 2.2 and 4.2 in the worksheet, which were added to understand student perceptions of the affordances of simulations for their learning. This was used to support the analysis of the affordances of simulations for sensemaking using the student discussion.

3.4.3 Qualitative analysis of audio transcripts

The transcripts obtained from the video was first transcribed using the video to identify speakers, and speaker tags were added to all speakers to identify talk turns and utterances. The transcribed transcripts were then translated from Finnish to English. During the translation process, it became evident that some Finnish words in the transcript had been captured incorrectly. I then reviewed the transcript in places where the translations did not make sense in the context of a science lesson and carefully identified the actual Finnish word being spoken, based on my basic familiarity with the language and with the help of the translation of the worksheet by the instructor, which gave the technical terms I needed to look out for. Using this technique, I retranslated problem aspects by using individual sentences in the EU digital tool. The final translated transcript was used as the basis of further analysis.

The translated audio transcripts were analysed in multiple layers to answer the two research questions. First, the transcript were analysed to identify structural features of the sensemaking epistemic game identified by Odden and Russ (2018) using a deductive coding scheme, based on the coding scheme developed by Haraldsrud and Odden (2024) based on Hunter et al. (2021). This involved coding the transcript for each utterance with a code that included entry conditions, explanation building or resolution. In this analysis, in continuation with Russ and Odden (2017) I defined an utterance as a conversational turn, where a change in speaker marks its end. The coding scheme is shown in the Table 2 along with some example data coded accordingly. The utterances without obvious codes were marked as no code segments.

Table 2. Coding scheme for structural components of sensemaking epistemic game, from Hunter et al. (2021)

Code	**Definition**	**Examples**
Entry Condition	*Initial voicing of a gap in understanding or a question leading to discussion.*	*"Is the tank safe in the extreme temperature of Mars if it is full? Yeah, that's right."*
Explanation Building	Students work together to iteratively build, compare and critique arguments to resolve the gap in understanding.	*"So, its pressure decreases more than it does with oxygen, so it has to be more stronger."*
Resolution	Explicit voicing of a conclusion to the entry condition	*"I mean, if it can withstand the upper and lower limits, and it's such a huge pressure variation now, then it's just fine."*

After the initial coding, sequences of student talk with high density of codes were taken for a more fine-grained analysis. In this step, the quality of explanation codes as described in the coding scheme in Table 3 given below were added on top of the explanation building codes.

Table 3. Quality of explanation codes within explanation building codes, from Hunter et al. (2021)

Code	Definition	Examples
Claim	A statement of a fact or an observation	*"But the volume stays the same for us."*
Evidence	Information or arguments supporting a claim	*"But there it is, freely adjustable, so it can be changed."*
Reasoning	Explicit connections and voiced reasoning between claim and evidence.	*"If the temperature is lower and they have some sort of mutual attraction, isn't it more likely at that stage that they'll collide with each other rather than not?"*

These episodes within the explanation building phase of sensemaking were further analysed using Russ et al.'s (2008) coding scheme for mechanistic reasoning, shown in Table 1. Initiator codes, given in Table 4, were then added on top, indicating the resource used to sustain discussion, for example a simulation or the worksheet activity itself.

Table 4. Initiator codes for identifying discussion resources, from Hunter et al. (2021)

Code	Definition	Examples
Simulations	The simulation is used to initialize or sustain a sensemaking process	*"Reset it, so we can start over.* *How does the volume change when you change the temperature?"*
Worksheets	The worksheet is used to initialize or sustain a sensemaking process	*"But then we need to focus on the fact that it said that the capacity of this tank is full."*

Further, for those utterances with an initiator code indicating that the simulation was used as a resource for sustaining discussion, affordances codes, as shown in Table 5, were applied on top of the simulation initiator code. These codes were adapted from the discussion on the affordances to sensemaking provided by simulations in Haraldsrud and Odden (2024).

Table 5. Simulation affordances codes, from Haraldsrud and Odden (2024)

Code	Definition
Exploration	The simulation encouraged students to explore a problem
Feedback	The simulations provided students with immediate feedback which kept students engaged in the task
Representation	The simulation produced visual output of a model which engage the students in the task
Uncertainty	The simulation produced output that came into conflict with prior experience, introducing a level of uncertainty

The final list of codes used is shown in Table 6 below.

Table 6. Code table with the list of all codes used

Code	Code Description
Sensemaking Codes	
Entry Condition	Initial voicing of a gap in understanding or a question leading to discussion.
Explanation Building	Students work together to iteratively build, compare and critique arguments to resolve the gap in understanding.
Resolution	Explicit voicing of a conclusion to the entry condition
Quality of Explanation Codes	
Claim	A statement of a fact or an observation
Evidence	Information or arguments supporting a claim
Reasoning	Explicit connections and voiced reasoning between claim and evidence.
Mechanistic Reasoning Codes	
Describing Target Phenomenon	Students state or demonstrate the particular phenomenon or result they are trying to explain
Identifying Setup Conditions	Students identify particular enabling conditions of the environment
Identifying Entities	Students articulate objects that affect the outcome of the phenomenon
Identifying Activities	Students articulate actions and interactions that occur among the entities
Identifying Properties of Entities	Students articulate general features of entities that are necessary
Identifying Organisation of Entities	Students describe or model where entities are located spatially and how they are organized
Chaining: Backward and Forward	Students use knowledge about the causal structure of the world to make claims about what must have happened previously or what will happen next
Analogies	students compare the target phenomenon to another to reason about the target phenomenon
Initiator Codes	
Simulations	The simulation is used to initialize or sustain a sensemaking process
Worksheets	The worksheet is used to initialize or sustain a sensemaking process
Affordance Code	
Exploration	The simulation encouraged students to explore a problem
Feedback	The simulations provided students with immediate feedback which kept students engaged in the task
Representation	The simulation produced visual output of a model which engage the students in the task
Uncertainty	The simulation produced output that came into conflict with prior experience, introducing a level of uncertainty

This multi-layered analysis allowed me to identify when sensemaking occurred, how it was related to mechanistic reasoning and to disentangle the role that simulations played while the students were engaged in sensemaking. Certain episodes which seemed rich in sensemaking components along with a well-defined role that simulations played in sustaining the sensemaking discussions, were taken for a richer analysis. In this analysis, I used analytic memoing to extract more meaning than possible from just coding. In this process, I focussed on the specific moves of students within the sensemaking epistemic game and created a rich description of the entire student discussion through this lens. Significant instances of how the simulations helped in sustaining sensemaking discussions were also included in this analysis to provide a level of nuance which afforded rich descriptions of the role simulations played in student sensemaking.

3.4.4 Quality Criteria

Quality criteria for a qualitative study determine evidence and provide justifications to the usefulness of the findings of the study (Lincoln & Guba, 1985). As opposed to a quantitative study where reliability and validity measures can be used to determine certain statistical robustness and verifiability of findings flowing from the data, in a qualitative study, further evaluative criteria is necessary to ensure verifiability and reproducibility of the findings from the data (Lincoln & Guba, 1985). Five quality criteria namely, credibility, dependability, conformability, transferability, and authenticity are discussed in this section to ensure that the study undertaken is rigorous.

Credibility

Cope (2014) defines credibility as the connections from the truth of the data to the interpretation and representation of them by the researcher. This criterion also increases the confidence of the objectivity of the findings of the study. In practice, for most qualitative research, credibility is supported when the researcher demonstrates the method of arriving at the findings through the data by means of the coding scheme and audit trails (Cope, 2014).

In terms of the coding scheme, this research study focussed on each turn of student talk. This is clearly defined, and every code assignment is backed by clear textual evidence by highlighting the relevant portion, so that interpretations are grounded in the actual data. The definitions of each code have been given along with examples from the data. The context has been taken into account when coding, so that meaning has not been lost. The coding scheme itself was created using relevant literature, so it is appropriate and relevant to the research questions. In this study, credibility was also established through clarity and transparency in defining the research question and the research setting.

Dependability

According to Cope (2014), dependability refers to the reproducibility of the research given similar conditions. In this study, dependability was established by being transparent about the nature of the sample and the method of analysis. selection of the sample and the method of analysis. By using similar theoretical framework, with a similar study, researchers would reach similar conclusions. This is because of the constancy of coding scheme as well as the logical framework within which the coding scheme was applied to the data, which was described in detail in the data analysis section. The findings of the study are also reported in rich detail with ample evidence from the data to support the interpretations provided by the researcher, which could add to the dependability of the study.

Confirmability

In reporting qualitative research, confirmability can be exhibited by providing rich descriptions directly from the data to depict findings. In this study, I have documented how my theoretical choice preferences might have influenced my coding through discussions on the theoretical background. Evidence has been provided from the data for each coding choice by giving examples from the data. The reported findings also include rich descriptions from the data. This has improved the conformability of this study. The findings also represent a wide range of data that was used for the analysis as many episodes of sensemaking were analysed and described.

Transferability

Cope (2014) defines transferability as providing evidence that findings that can be applied to other settings or groups. The sampling for this study was a convenience sampling the instructor was already engaged in sensemaking practices in their classroom. This makes transferability to other contexts a limitation, as this was done in a particular context with a particular instructor and thus the findings may not be generalizable. But since the sample collection and theory were not developed simultaneously this study could be seen as confirming some aspects of the framework developed in Haraldsrud and Odden (2024) and Hunter et al. (2021) along with establishing the usefulness of analysing sensemaking processes through an epistemic games framework as developed by Odden and Russ (2018), within the context of this particular classroom. In that sense, the transferability of this study is also rooted in the fact that this theory was developed in a different context and thus its applicability within this study itself is a measure of its transferability. More studies in more contexts are needed to make the results more generalizable, and it could be a direction for future research. The description of the research setting, activity design, the process of analysis and the interpretation process of the findings presented in this study could be replicated, which could also establish a sense of transferability of this study.

Authenticity

According to Cope (2014), authenticity refers to the fact of expressing the experiences of the participants to the reader in as faithful a manner as possible. In this study, this is done mainly through the use of participants discussion in the rich descriptions of sensemaking episodes offered in the findings. A limitation within this is that since the reported dialogue has been translated to English, nuances in Finnish might have been missed and similarly, nuances of the English activity might have been missed in the translation to English. But more broadly, the findings reported in the study stay away from generalizations and only induce evidence for particular episodes to be part of the sensemaking process that can be made based on the evidence from this data. This indicates the rootedness of the findings within the context of the data, which showcases the authenticity of this study.

4 Findings

This chapter will present the results of the analysis for both the research questions,
RQ1: How does sensemaking happen in a university chemistry class while using computer simulations as a pedagogical tool in an inquiry-oriented lesson?
And
RQ2: What are the affordances offered by the computer simulations that promote sensemaking in a university chemistry class?

Firstly, the results from the TAM surveys are presented with means for all sections within the three surveys. As given in Table 7 below, the survey results show that there is a general acceptance of simulation use in their learning as well as their future teaching, by the student teachers as indicated by the high total TAM scores.

Table 7. Results from TAM surveys

Construct	**Survey type**	**Means of Likert scores (1=least , 5=most)**
Perceived Usefulness	*Pre Learning*	4.16
	Post Learning	4.02
	Post Teaching	4.23
Perceived Ease of Use	*Pre Learning*	3.60
	Post Learning	3.50
	Post Teaching	4.14
Perceived Interest	*Pre Learning*	4.00
	Post Learning	4.03
	Post Teaching	4.22
Total TAM Score	*Pre Learning*	3.94
	Post Learning	3.87
	Post Teaching	4.20

The students perceive that the simulation is useful, but the means are lower for the perceived ease of use, which may show that the students are not very familiar with simulations currently, though they are eager to use it and find it beneficial. The chart in Figure 2 below shows the same data, highlighting the difference in the perceived ease of use in their learning versus in their teaching. Students seem to be more confident in the ease of using simulations in their teaching than in their learning. This may be because they might feel that simulations for school level science may be simpler to use than the ones they used.

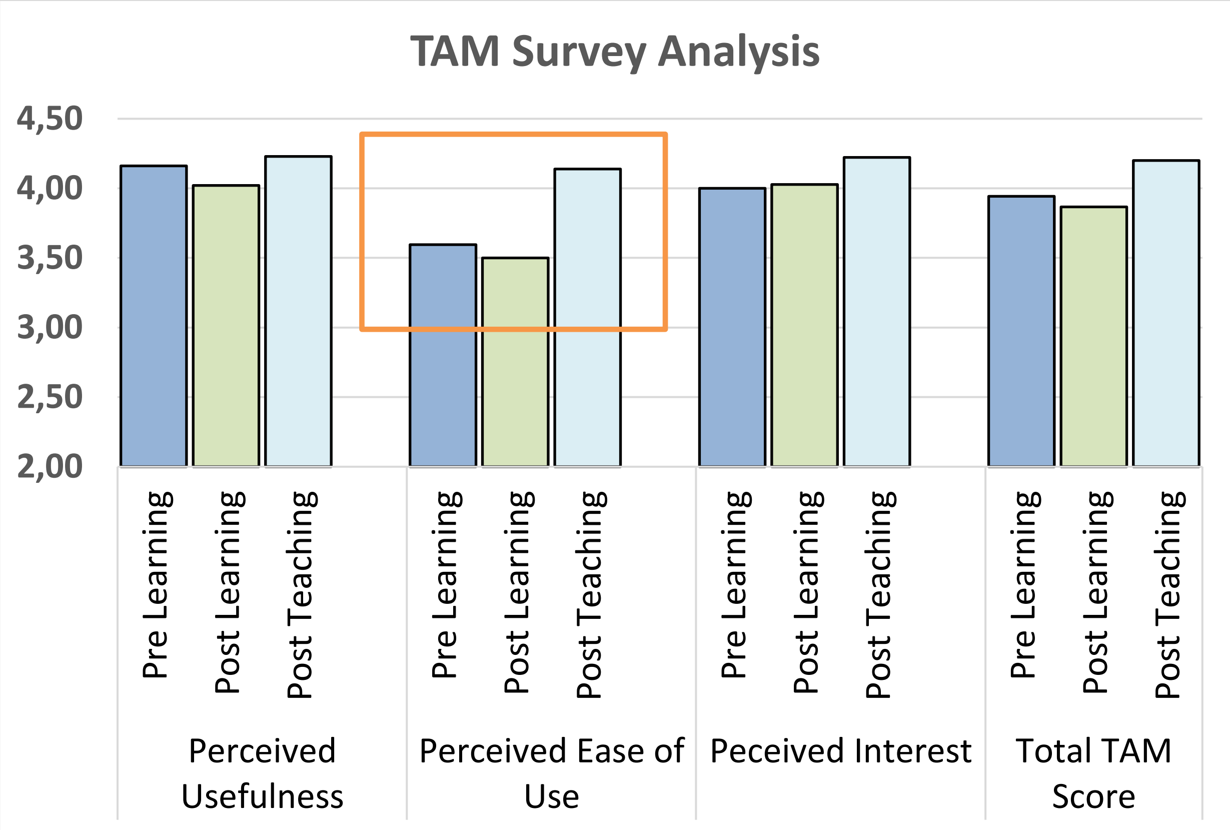

Figure 2. Difference in perceived ease of use in teaching versus learning

In general, the teacher students showed that they accepted simulation use more for teaching than for learning, but both levels were high and showed an acceptance of simulation as a technology in educational settings, indicating that the simulation may not be a barrier in their sensemaking due to unacceptance of the technology itself.

Next, the results from the post task survey to determine student perceptions on sensemaking using the simulation in real classroom contexts is presented here in Table 8.

Table 8. Student teachers perceptions on sensemaking using simulations

Construct	**Survey type**	**Means of Likert scores (1=least , 5=most)**
Simulation aided sensemaking	*Post Learning*	4.32

From the high mean score, we can see that the student teachers found the interactive simulation to promote sensemaking in real contexts. Since the students were actively involved in problem solving using the simulation, it may have promoted a sense of agency as well as helped in their visualisations of gases leading to this perception.

Next, results from the thematic analysis of questions 2.2 and 4.2 from the worksheet are presented. These questions probed the students to answer how simulations helped them with solving the problems. Two themes originated from the answers from the 5 groups. Firstly, students expect the simulation to be closely related to the problem they are solving, which shows in some frustration that the volume could not be made constant in the simulation. Secondly, Students seem to see the representational affordance of simulations as being particularly useful in their sensemaking. These two themes will be developed in the discussion section combined with results from the analysis of student discussions.

The analysis of worksheet questions for mechanistic reasoning yielded some results which are presented next. It is seen that students typically used higher-level codes while writing their explanations, showing fluent use of mechanistic reasoning. Lower-level codes are mostly missing from student written work. There is evidence of chaining in most of the answers, showing that students can causally link microscopic entities to macroscopic gas behaviour. It is seen that in questions where students have to check their hypothesis using simulations, evidence for mechanistic reasoning is lesser as compared to questions where students are asked to generate hypothesis, which show ample evidence for mechanistic reasoning. These results will also be discussed in the context of student discussions later in this study.

4.1 Results from analysis of student discussion transcripts

Finally, the results from the analysis of the transcripts are presented in the form of selected cases of sensemaking as identified through the data analysis method provided in the previous chapter. The episodes that are presented in this chapter are rich in construction and critique within the explanation building phase of the sensemaking epistemic game. They also feature the use of the simulation as an important factor in sustaining discussion with which I hope to illuminate the role simulations play in sustaining sensemaking discussions. The analysis of each case enabled me to give a fine-grained description of the trajectories of students' sensemaking aided by interactive simulations and the affordances offered by such simulations for sensemaking. Presentation of sensemaking episodes in this manner is a suitable method to explore the sensemaking process as it enabled me to describe with rich detail the diverse ways in which sensemaking progressed and the multiple ways in which simulations helped the students in their sensemaking.

All the episodes presented have student dialogue from the translated transcripts to provide evidence for my interpretation and claims. In the following episodes, the students' dialogue is highlighted in italics. The entry condition and resolution for these episodes are mentioned in the analysis. The episodes presented were chosen as they had a high prevalence of sensemaking behaviours as well as offering evidence for the sensemaking epistemic form in the student discussions in the form of by high level of construction and critique within a robust explanation building phase. I have also identified the mechanistic reasoning codes assigned to student dialogue, within these snippets of dialogue, by adding them within brackets {}. These codes highlight the level of mechanistic reasoning to provide further evidence of robust explanation building, which is an important hallmark of sensemaking. Further, the episodes provide a wide range of student moves within the sensemaking epistemic game, which may give a broader understanding of how sensemaking progresses in an inquiry-oriented lesson. The episodes are organised according to groups. After analysing the moves and the trajectories of sensemaking within each episode through the use of student dialogue, I have added my interpretation and a summary of important aspects to be highlighted in each episode.

4.1.1 Episode 1 – Group 1

The first episode in the analysis is from the discussion of Group 1 consisting of 3 students, as they try to answer question number 3 from the worksheet. I call the students Andrea (A), Brenda (B) and Clara (C) as pseudonyms to protect their privacy. In this episode, the students are discussing the effect of non-ideal gas parameters like particle mass, particle size and particle attraction on macroscopic properties like volume, pressure and temperature. The discussion starts with one of the students entering the sensemaking frame by articulating the problem statement and adding that "It's going to be tricky." This sets the stage for the sensemaking episode that follows. Going by the worksheet, they first try to hypothesise what could be the relationship between volume and particle mass, without using the simulation.

C: As the mass increases, the volume will probably be greater than with the starting mass of the particles, because that's the relation with mass.

B: On the other hand, the volume doesn't necessarily increase just because the mass increases.

A: If the mass increases, it'll put more force on the piston. {chaining (C)} *That's how I'd think of it. Because if it collides with it, the forces will be greater.* {Identifying entities (IE), Identifying activities (IA), Chaining (C)}

The claim by Clara, that as the particle's mass is increased the volume will increase, is critiqued by Brenda. Andrea then gives evidence to Clara's claim with an argument for why Clara might be right by stating that particles with more mass will exert more force on the piston. This explicit connection between claim and evidence demonstrates reasoning by Andrea. The discussion continues with the students discussing the other macroscopic properties.

B: Does greater mass mean greater pressure? Temperature?

A: I can't say anything about that.

B: The temperature also rises maybe, since the forces are greater. {C}

A: If the temperature rises, the number of collisions increases. {IA} *But I don't know how that mass would affect the temperature.*

Here Andrea faces some confusion between the number of collisions and the force of collision of each particle. She states that if temperature rises, then there will be more collisions, but in her original line of thinking the increased mass affected the force of the collisions and not the number of such collisions. This creates an uncertainty in her mind which she articulates as being not sure how mass affects temperature. Clara tries to clarify their discussion next.

C: If there is less mass, then it is presented with a lower pressure.

A: What? Let's have a look at that. There are generally a few more collisions because there is more of it, as the large particles hits

B: more and more in the same space.

The discussion seems to become about particle size than mass. The students seem to understand that if mass is larger, the size is also larger without explicitly addressing that they are different properties of the particles.

C: Is it more volume? If the size increases but the amount stays the same, is it a larger volume? If so, volume is related to particle mass.

A: If it can change, then surely it requires more volume. That's it. Temperature. I think we need a higher temperature. Because the size usually does not change without changing their mass. {C} *Would it be worth comparing the substances they're made of, given that others are composed of them too?*

Here, Andrea makes explicit the connection between particle size and mass which the students have been making implicitly. Now, she thinks about the material properties, but seems to not think that particle mass and size are related to material properties.

C: Think about these simulations. It's a little too much. I thought common sense would help.

By now, Clara seems to be slipping out of the sensemaking frame and states that “It’s a little too much”. She seems to make a distinction between common sense and simulation, which may show that she thinks of the simulation as something which can present scientific concepts beyond common sense. This indicates that she might think that using the simulation to test these hypotheses might be useful.

A: Volume, pressure and temperature range of particles of attraction. Again, there will probably be more collisions where the attraction is high. {Identifying properties of Entities (IPE)}

C: You can do that with common sense.

A: On the other hand, if they attract each other, they will probably more easily form molecules with them. {C, IPE} *They stay together. Yeah, that's right. It's all about it.*

B: So that they just form molecules?

A: Let's just say that they can't form, that they just collide and then they get separated. {IA} *If they collide, they cannot form. They cannot form because are separated. If they have a high attraction, is it just that there could be a single point where they all are?* {Identifying organisation of Entities (IOE)} *Perhaps that’s the question. If it is completely theoretically done, then if they have a high attraction, then it should only be so that all the oxygen is in that corner and we are all suffocated.* {C} *We’ll see.*

The next question though seems to stimulate some discussion from Brenda and Andrea. Andrea states the question and claims that higher attraction means more collisions. But, she also thinks that the particles can form molecules and stay together, which would mean lesser collisions. There is a tension in her mind since she goes back and forth between these concepts, as she seems to think that collisions between particles involves them separating after the collision. For her, colliding particles always separates and cannot form molecules. So, the fact that particles with high attraction can form molecules is in conflict with her understanding earlier that they collide more often. Thinking through, she claims that if the particles have a high attraction, all the particles will come together, not forming molecules but completely isolated in a corner. She uses her argumentation about them sticking together as evidence for her claim, demonstrating some reasoning.

C: That's a really good idea. In theory, it sounds like this could be the case. Yeah, that's right. Now they are gathering.

B: It's a ball. Oh, that's nice.

A: I put that theory there too.

B: Yeah, that's right.

Here they seem to end the discussion, with a resolution that they will write that the particles all gather in one location. Let us now see how they discuss this further with the help of the simulation.

A: The effect of particulate mass on volume, pressure and temperature.

What changes did you notice when the particle mass increased? All right, let's go.

B: Now we can.

C: Has it started now? Yeah, that's right.

A: And then I'd turn it on so that it can. We'll do our own assessment of that.

Here the students use the explorative affordance of simulations, to discuss and critique their argument previously. They clearly state that they are assessing their hypothesis using the simulation output. This shows that they believe that the simulation output will show the reality of the situation and they have trust in the output.

B: And we'll change it first. The particle mass is increasing. {IPE}

A: I'd know the pressure right now as well. For us, that pressure doesn't change. Oh. Well, that can be done over there. The particle mass is increasing.

B: Now there is deceleration. {IA}

C: Yeah, that's right. We did write that, didn't we? This wasn't done? If there is more mass, then it will be slower. {C, IPE} *Didn't we do it? Yeah, that's right. Or didn't we do that?*

In this first part of the assessment, the students use the simulation as a representational resource drawing upon the representational affordance to see that when the particle mass increases it seems to slow down the particles. They offer some amount of evidence and reasoning for their claims by restating their arguments for why the particles will move slower.

B: Or did I write it? Yeah, that's right. It's slower. Yeah, that's right.

A: It's in there. The temperature must be higher. A large particle has the same amount of energy. {IPE}

B: But nothing else changed. At least it looks like it. No, no, no, no. These things just don't change. Temperature and pressure and volume remain constant.

The fact that temperature has not changed goes against their hypothesis from before, where they argued that temperature would increase. There is some unexpected outcome from the simulation, which shows that the macro properties do not change due to change in particle mass. This highlights the uncertainty affordance of simulations which can lead to sustained sensemaking. But in this episode, the students quickly move over to the next question. They seem to use the simulation output as the clinching evidence for an argument and fail to engage further in explanation building or mechanistic reasoning to tease out why this might be the case.

C: Shall we see the next ones?

A: The particle size is increasing. {IPE} *Particulate size. Let's take a look. I'm gonna put these up right now. All right, let's go. We wanted to change the particle size. That's it. At least the volume is increasing.*

B: The volume increases. The volume is increasing. The volume increases.

C: But it's slowing down.

With the variable of particle size, they see that volume increases, which is in line with their discussion and reasoning from before. Here too, they stop discussing as soon as the simulation output is viewed.

A: Particle attraction. {IPE}

B: Does anything change here? Isn't that a little lower? That volume is decreasing.

A: The volume is decreasing. But the others they don't change. See the rest of them forming such clusters! {IOE} *Like I said!*

B: Yeah, that's right. They go like that.

B: What is it? A little something like that.

A: yep. Getting stuck.

In this exchange, the students use the simulation as a representational resource and use the clustering of particles as evidence for their previous reasoning. The visual output of the simulation, which corroborates their initial hypothesis seems particularly relevant for Andrea, who came up with the reasoning and evidence that particle attraction would make the particles come together in a corner.

A: What should I write? Yeah. I've got it right here. But why does the volume decrease? This is weird. Well, probably because they collide with each other more than, say, with that wall. {IA, C} *Because they have to make those collisions with the piston, don't they? For the volume to increase.* {IA, C}

B: Yeah, that's right.

C: And so it can usually be if the pulling force increases. Resulting in a smaller area. {IPE, C}

A: Yeah, that's right.

Finally, noticing that the volume has decreased makes Andrea think it is weird. This is also because, they thought that the volume would increase due to higher number collisions when the particle attraction is higher. There was conflict in Andrea when she thought about the clumping of particles versus collision of particles. But, after getting the feedback that volume did decrease, and particles did clump together, they concluded that this was because the particles collide with each other, while for volume to increase the particles must collide with the piston wall. Thus, they reason that if the attraction between particles increases, the particles collide less with the piston resulting in lower volume.

In the explanation building phase of their discussions, the students showcased many of the characteristics of building scientific explanations and mechanistic reasoning. Specifically, they identified that the way the entities (particles here) are organised can be used to reason about what will happen in the future using the claim, evidence and reasoning structure. They also describe the properties of these entities and the activities of these entities, such as colliding and moving slower or faster. While building a complete scientific explanation, they also use their knowledge of the causal structure within the framework of particle behaviour to predict and hypothesise about the system. This shows compelling evidence that the students use mechanistic reasoning. Also, looking at the codes of mechanistic reasoning in the transcripts above, higher level codes such as chaining, identifying organisation of entities, identifying properties of entities and identifying activities are present through the explanation building phase. This builds confidence that the students engage in mechanistic reasoning and sensemaking rather than answer-making for this part of the worksheet.

The discussions around particle attraction also show that the uncertainty factor as a simulation affordance can be useful in sensemaking discussions, along with the immediate feedback that the simulation provides. In the case of particle attraction, though the simulation confirmed one part of the students' thinking, the volume decrease went against their hypothesis, which led them to discuss and build an explanation for why it is so, consistent with their thoughts on the behaviour of particles. Thus, the simulation output helped them reconcile their thinking about volume, a macroscopic property, with the clumping of particles, which is a microscopic behaviour. Thus, the simulation helped them bridge thinking about how microscopic behaviour can affect macroscopic property change, which is essential for learning concepts in chemistry.

4.1.2 Episode 2 – Group 2

The next episode examines the sensemaking process of Group 2 also consisting of 3 students as they explore the fundamental gas laws through the relationship between volume, number of particles, temperature, and pressure through question number 1 from the worksheet. I call the students Aino (A), Birgitta (B) and Cia (C) as pseudonyms to protect their privacy. The main theme which emerges from this episode is the collaborative construction of a microscopic causal model to explain macroscopic observations, specifically focusing on how particle motion acts as a mediator between temperature and volume. The students' main move in the sensemaking trajectory involves negotiating the definitions of the variables, specifically identifying the relationship between the volume of an individual particle and the volume of the gas. The students enter the sensemaking frame by restating the problem from the worksheet.

A: So the volume increases as the number of particles increases. Or rather, the volume increases as the volume of the particles increases, not as their number increases. {C, IPE, IOE}

B: Why are these here? Well, well, so the volume increases.

C: Yes, this is a sort of expanded volume. And then you put even more of the particles in there. The volume increases as the number increases. {IE, C}

A: Well, that's good. Yeah, but, I mean, that bit means it sort of has a big effect. It's not directly about putting a bit in there. {IPE}

Aino claims that the volume will increase with an increase in the number of particles. She argues that this is because the volume of the particles in total increases leading to an increase in volume of the gas. This is not quite scientific as the actual volume of particles is negligible when compared to the volume of the gas. In this case, the students may have been misled by the representation in the simulation, since the simulation shows the particles to be quite magnified and related in magnitude to the volume of the gas. Thus, even though representational affordance of simulation might help in students' sensemaking, it can also cause misconceptions if the students are not aware of the limitations of the simulation model.

C: I mean, you sort of have to connect the dots. Reasoning. Let's justify it. Yeah, yeah.

A: It's just that when I write it down, it's easy to write. We want to justify it again. So.

B: Well, then.

B: That doesn't matter, does it? Is that detailed enough? That's all there is to it.

The students do not try to critique Aino's claim, and they seem to accept that this is why the volume changes. Then, they move on to look at the effect of temperature and volume.

A: The temperature increase, increases the volume. Well. So. thermal motion increases. Or the particle's motion increases and. Yes. {IPE, IA, C}

B: This rise in temperature makes the particles move more, sort of. {IPE, C}

C: Right? Yeah. Yeah. It sort of increases the pressure, and that pressure does that. Doesn't it?

A: And I could add that if the volume didn't change, then the pressure would increase. The temperature would rise. Right. Like, this temperature would rise. {C}

B: When the temperature rises, they collide more with the bottom of the piston. {IA, IPE, C}

C: Lovely to hear that. Or let's think about it like this. If we make the space smaller, it'll bump into things. And that's fine. And then if it refers to the pressure of the vessel. {IPE, IA, C}

A: On the other hand. I mean, if the volume is constant, it won't grow. {C}

B: Right. If the pressure stays constant, then the volume is changed, then.

Aino claims that as temperature increases, the volume increases. As evidence for this claim, she brings up the thermal motion of the particles. Birgitta, supports Aino's claim by arguing that the temperature increase makes the particles to move more. Cia builds on this by adding that the increase in particle motion increases the pressure. Aino uses Cia's claim and modifies it to fit within the framework of volume by stating that if volume was constant, the pressure would increase but since the volume is not constant, the increase in temperature makes the volume grow. Birgitta gives more evidence to support their claims by indicating a mechanism by which higher temperature may lead to more collisions at the bottom of the piston. She may be hinting that that is what causes higher pressure that Cia was talking about. Cia then backs Birgitta's reasoning by imagining what would happen if the volume was smaller and it is easier for particles to bump into the piston, which she states as causing the pressure. Thus, the students build on each other's explanation presenting evidence and reasoning to come to a conclusion. They also use mechanistic reasoning to indicate the causal mechanism that links the microscopic events at the particle level to macroscopic behaviour in terms of increasing pressure or volume. The students next move onto the relationship between pressure and volume, which they have already been hinting at.

A: pressure.

B: So when the pressure increases, it takes up that volume. You can expand from a small volume? Yes. {C, IPE}

C: When it's pushed, there's more force there, and that force is generated by those particles. {IA, IOE, C}

A: So, a collision of sorts. That's it, isn't it?

C: Yeah. The pressure. Well, shall we put that in? As pressure increases, collisions between particles increase. So that the force. So when the collision forces are greater. And in a smaller volume. As the pressure increases, the particles. They're aimed at the piston. The impact forces increase. The pressure increases, causing it to reduce. {C, Identifying Setup Conditions (ISC)}

Birgitta starts the discussion by claiming that as pressure increases the volume expands. This is contrary to the students' discussion when they were discussing the effect of temperature. Cia might have missed this discrepancy and tries to understand the underlying mechanism of increasing pressure. She links higher pressure to more force generated by particles on the piston. She creates an explanation, linking the increasing collisions to a greater force. She also uses their previous understanding that volume decreases, to indicate why increasing pressure may decrease the volume. She seems to be saying that in a smaller volume, more particles may be aimed at the piston, so that as the volume decreases, pressure increases. This seems to be confusing cause and effect as she started off her claim with pressure being the independent variable which was being manipulated. Thus, this exchange seems to bring some conceptual confusion around pressure and volume. Next, the students use the simulation as a feedback resource to see how the relationship between pressure and volume plays out.

C: Yes. The surface area is smaller. P is F/A. If A decreases then p increases. Just write that P is F/A. {IPE, ISC, C}

B: How is the area decreasing? Because it's descending? The system.

A: The system area is. So there must be something going on. Relative area, perhaps. Does it or doesn't it? Well, that's it.

C: Here's the pressure. Here's the first area. So yeah, so when that's done with this. Then here it is. That's the end of it. {C}

B: Something like this. Let's move on to the next section.

Cia claims that as the surface area decreases the force stays the same, causing the pressure to increase. Birgitta asks her for clarity on how she can say that the area is decreasing. Cia uses the simulation's feedback and representational affordance to highlight what she has claimed in the simulation screen. She uses the comparison feature of the simulation to explicitly show what she means and why that means the pressure is increased. Here, she seems to be using the simulation output as evidence to back her claim and as a resource for reasoning. Next, the students use the simulation to check their reasoning and hypothesis about number of particles and temperature too.

C: Volume and molecules. Right, so. Ah, so this is it. Right, lift this up. Ooh, there it is. Like that, just a few more. Right, I'll put more here. What? Well, there's less here and more over there.

A: Volume. Is it the same in these? Is this like this one here?

B: What does that mean? Oh, right, I see. Right then, okay. Right, there's more there, it's bigger there. Volume. And the ones with lesser particles are in the smaller one. {C, IPE}

C: Are the others the same as these sometimes? I mean, the other sizes, yeah.

B: Did the simulation just confirm the hypothesis, or did it make you change your mind? Well, yes, it confirmed it. Do I need to explain this in more detail? It confirmed and illustrated it. Do I need to explain anything about that? Um.

A: As the number of particles increases, its volume increases. {C}

The simulation seems to confirm their original hypothesis. They do not linger on their original reasoning that the volume increases because of the increasing volume of the particles. Since the simulation also reinforces their misconceptions, by representing the volume of particles to be of a similar magnitude, it may not help in the students overcoming this misconception. They move on to the effect of temperature on volume.

B: So then I'll raise this temperature from the other one somehow. I don't really know what's going to happen, you know.

A: Doesn't this work now? But if I press this now. Ah, there we go, now it's perfect.

C: Well, it does grow quite a lot. Uh uh, just like the starting point.

A: Right. And now we can basically watch it here.

B: Is the temperature rising? Yeah, it's actually higher, so it's kind of like that.

C: Yeah, now it's not off again. You can tell the temperature is rising. Is the temperature rising? Yeah.

A: For a small increase in volume.

The students here use the representational affordance of the simulation to sustain their sensemaking. Birgitta states that she is unsure of what the effect will be, and the fact that they can test it and actually visualise the effect seems to be helping the students remain in the sensemaking frame. The students reach a resolution in this episode of sensemaking by noting down that the volume increases with an increase in temperature.

This episode highlights the fact that explanation building phase of sensemaking is helped by simulation and the explorative, representational and feedback affordances it offers. It also highlights the limitations of simulations as the difference in representations and the actual reality (particle volume) may cause and sustain misconceptions in students. Even though the students' mechanistic reasoning can be deduced by the presence of higher-level codes, the explanation building in this episode showed some confusion about cause and effect. On the other hand, the representational affordance of the simulation strongly helped the integration of microscopic particle level reasoning in terms of particle collisions and its relationship with pressure and volume. Thus, the affordances of simulation seem to aid and also hinder the possibility of conceptual learning.

4.1.3 Episode 3 – Group 2

The next episode is also from the discussion of Group 2 (Aino, Birgitta and Cia). They are discussing the effect of non-ideal gas parameters like particle mass, particle size and particle attraction on macroscopic properties like volume, pressure and temperature through question 3 from the worksheet. The narrative highlights collaborative critique and mechanistic reasoning within the explanation building phase of sensemaking epistemic game. The students enter the sensemaking frame with Aino reading out the problem and stating “Yeah, these are tricky.”

A: I mean, particle mass.

B: And in a way, the particle mass affects it in that greater the particle mass it has greater pressure. {C, IPE}

A: Yes.

B: It depends on whether the volume increases on its own.

C: It can work that way.

The students discuss if greater particle mass causes greater pressure. Next, Aino reasons that higher mass of particles cause greater forces in the system, and these forces are proportional to volume, temperature and pressure.

A: Do we want to state that a greater mass causes greater forces in the system, which is directly proportional to volume and temperature, which in turn is proportional to pressure?

C: When the mass increases, the volume increases more. {C}

B: This can be seen

A: And temperature is the part of heat that has been converted into kinetic energy. {IA}

B: Can we put it like that?

Aino brings in the kinetic theory of heat as a resource for why she thinks temperature increases when mass increases. She equates kinetic energy of the particles to their heat content. Cia agrees with Aino, reframing her point about why more mass might mean more energy in the system.

C: Right, your point was that there’s just more energy going directly into it, when that particle has more mass. {C, IPE}

A: Something like that.

C: If that directly affects, how heavy things are matters.

A: Wouldn’t we assume in this situation that it increases those forces, meaning the pressure would increase if the forces increase, but the volume remains the same? {C, ISC}

C: I’m not really sure about that.

A: How should we distinguish between these? Well, let's just assume that the increase in mass increases the magnitude of the forces involved in those processes, the systemic magnitude of those forces.

B: Can we put it like that? Yeah, good.

C: Because the additional mass creates, as it were, the force of the impact. {C, IPE, IA}

Here, Aino tries to make her reasoning more coherent by explicitly connecting her claims and evidence by arguing that the volume may remain same while the pressure increases because of the increase in particle mass. They resolve this discussion by claiming that the additional mass of the particles increases the force with which the particles impact on the piston, and that increases the pressure. Next, the group moves onto discussing other variables such as temperature and their relationship with particle mass.

B: On the other hand, more energy is needed there. How much of energy is used for movement? So if we have the same amount of energy available, we can't really manage to use it move all heavy ones. {C, ISC, IPE}

A: It can be moved more slowly if we don't have enough energy. {IA, IPE, C}

C: We don't have that energy anymore, but just like that.

B: Well, but I'm not really convinced in the fact that this large mass requires more energy to move.

Here, Birgitta reintroduces the aspect of kinetic energy that the students had used earlier, to understand what happens to temperature. She claims that if the same amount of kinetic energy is present, a system with heavier particles will move less. Aino and Cia also back up her reasoning, building on it by arguing that if the energy is less, then the particles will move more slowly. Birgitta is uncertain though and hedges her statement by saying that she's not really convinced. This uncertainty is then used productively by using the simulation to check for what they have been discussing so far. The explorative factor of the simulation seems to be sustaining the sensemaking when the students faced some uncertainty in their thinking.

A: We could probably try something with the particle mass to see if pressure keeps increasing. {IPE, C}

B: Yeah.

A: So, over here, we actually need a bit more particles here in the space here.

B: Well, OK, I mean, it does have an effect overall, but that's not the point.

The students use the simulation to check if their reasoning is correct. This underscores the feedback affordance of the simulation, since the students modify their reasoning based on the feedback from the simulation output.

C: Then, if we keep the volume constant, pressure increases as the particle size increases. {IPE}

B: If the volume stayed constant, then increase in mass would increase the pressure. {C, IPE}

C: Is it heat as well? I don't know.

A: You could say that, if you like.

The students seem to have noticed that the particle size changes caused a decrease in volume and reason using this as evidence that if the volume stayed constant, then the pressure would have increased. They have linked particle mass and particle size together, without explicitly mentioning it. However, they come back to it and articulate why they think particle size and mass are correlated.

B: Well, larger particles are often a bit heavier, aren't they?

A: Well, of course the first one is a little bigger; you can tell just by looking at it that it's heavy.

B: Right, let's go through this one, and then just like this for temperature.

Thus, their linking of particle mass and size is articulated explicitly, and the simulation representation is used as evidence for this link, though it is based only on a feeling ("*you can just tell by looking*") and not with the actual output of the simulation. Thus, prior expectations and conceptions affect the students' observations in the simulation, as well as on their reasoning. Coming back to temperature, the students try to see if the increase in mass (or size) changes the temperature.

A: Does it change? Does it change? Maybe it could be a bit more like that.

B: When you have better mass, the pressure increases. We can't reset it, though. So, the temperature in this situation remains the same. The pressure increases as the mass increases. {IPE, C}

C: So how did that match up with what we assumed the situation would be? We assumed that everything would change somehow.

A: We assumed that the situation was a source of pressure, increasing pressure.

C: We got that pressure right.

B: We assumed they would change temperature, but it hasn't.

A: So let's start by saying what changes we observed.

The students resolve this episode by stating that increasing the mass led to increase in pressure, but no increase in temperature. Their discussion on kinetic energy, which seemed to have potential for sensemaking about temperature changes is not sustained after the feedback from the simulation goes against their expectation. Thus, in this episode, the simulation may have been used as an expression of authority and the sensemaking epistemic game ended with a transfer to authority-asking at the end.

This episode illustrates the sustenance of sensemaking by the students by using the simulation's affordance of exploration and feedback. This was especially highlighted when the uncertainty expressed by Cia was used by Aino to enter into sustained sensemaking using the explorative affordance of the simulation and by checking the feedback through the resulting output. While the episode highlighted robust explanation building by the students using construction and critique, to build scientific explanations with the use of mechanistic reasoning, this episode is not ideal as sensemaking since the final resolution is achieved with more of an answer-making frame, even though other structural elements of sensemaking and the epistemic form is present. This episode also highlights the ephemeral nature of sensemaking as the students quickly go back to a answer-making frame where they use the simulation as an expression of authority, and do not use the uncertainty provided by the output which was in conflict with their explanation building with regard to the effect of particle mass on temperature.

4.1.4 Episode 4 – Group 3

This episode examines the sensemaking journey of Group 3 consisting of three students (Pseudonyms: Ayden (A), Betty (B) and Carl (C)) as they evaluate the safety of an oxygen storage tank on Mars, through question 2 from the worksheet. This episode is characterized by the students' attempt to bridge macroscopic safety concerns with microscopic gas behaviour, utilizing theoretical resources like the ideal gas law while simultaneously critiquing what they perceive to be the simulation's limitations. The students enter into the sensemaking frame by articulating the question from the worksheet and the students go into a discussion on whether oxygen can become a liquid at the temperatures involved.

A: Hey, is it safe on Mars at those temperatures? Explain.

B: The first thing that comes to mind is liquid oxygen, or rather, the fact that it's liquid, which I think is below minus a hundred degrees. {ISC}

C: What is it that makes it form into a liquid? What is the melting point of oxygen? I think the liquid form is something like, isn't it around 100, or 120? I reckon liquid oxygen is somewhere in that ballpark. {IPE, IOE}

A: But, I mean. Does it actually go that low? I mean, liquid oxygen is really cold. Well, maybe in space it could. {C}

The students try to figure out if the temperature in space is cold enough to liquefy oxygen. They then switch track by claiming that in the vessel, the volume remains constant so the pressure in the vessel is more relevant for the problem.

B: But if we think that the volume stays constant, then whatever's affecting it there is pressure. {ISC, C}

A: Yeah, could it have an effect if pressure builds up and forces it into a smaller space, so it rises for a moment? I mean, there'd be like positive pressure there. {IA, IOE, C}

C: Yeah. But does that mean that, well, no, if it gets warmer, then it doesn't affect it.

B: Well, not if it goes below minus a hundred? I mean, a negative effect? Yeah, yeah, right.

A: Yeah, if it were to change in a way that was, like, dangerous. But it was meant to be a gas, wasn't it?

B: Well, I mean, maybe there's more of a risk that it'll sort of collapse inwards. It creates a sort of vacuum. {C, IA, IPE}

The students address the connection between volume and pressure here by reasoning that if the pressure builds up it may force the oxygen into a smaller space. Betty builds on this argument by critiquing it. She states that instead of pressure building, it might reduce so drastically when the temperature falls, that it might lead to the tank collapsing inward due to the creation of a vacuum within the tank. The students then face a moment of uncertainty in the way the problem is framed in the worksheet.

B: But that, I mean, what confuses me is that it's full of oxygen, like that. What do you mean, full of oxygen? Yeah, how much is there actually? {ISC}

A: But has it been filled up so that it's been at zero degrees? Yeah.

B: Those are full to the brim with oxygen.

C: Just think, we do have these options, which are significant when there's something going on at the moment. But what if it goes into positive territory? What does that mean then, if it's sustainable? That's it.

A: Then it'll probably become overloaded. Then it might explode. {C}

The uncertainty over the temperature at which the tank was filled initially sustains the students' attempt at making sense of the problem here. They seem to claim that if it is not filled at 0 °C (the higher temperature range), then the tank may become overloaded as the pressure increases with increase in temperature and that the tank may explode because of this change in temperature. Thus, the initial setup conditions become very important for identifying if the tank can withstand the pressure. In their written work, the students also include the argument that the explosion is due to the increased movement of the particles resulting in more collisions, which increases the pressure. Thus, the students seem to link the behaviour of particles to the macroscopic variables like pressure. Next, the students try to reason how much the pressure will change using the ideal gas law as their resource.

C: How does it hold up? I'd be more interested in how much pressure it can withstand.

B: What is it? P, V, N, R, T.

A: Isn't that the Pressure.

B: Yes it is. N, R, T. So the amount of V stays the same the whole time. R stays the same. But T changes. {ISC, C}

C: Yeah. Volume. The volume is the same. But the pressure might change.

B: Yeah. So it might increase.

C: Yeah. Well, sort of.

A: Yes, in principle that's what we're looking for.

B: Or is it just the temperature that affects it? No, it's the pressure. I mean, if the temperature rises, the pressure increases. {C}

A: Yes, yes. But then it's just that. It's because of the temperature.

C: Right, so in practice it's only the temperature that changes. Which is why the volume changes and the pressure changes too. {ISC}

The students notice that since the volume remains the same in the tank, only the pressure may change if the temperature changes. They continue discussing this and reason that the pressure increase is only possible with an increase in temperature and other factors do not affect it.

C: OK, let's think about that. Yeah. I'm mainly wondering if it's there at all. Is the thing here that if it is actually liquid in there. If the pressure is so high that it actually stays, you know, as a liquid in there. {ISC, C, IPE}

A: True. Just think, if it's like a big cold mass of liquid.

B: That's so true. Because if you think about welding or gas cylinders, for example, what's actually inside them is a liquid. {A} *But in these bottles that people use, I've no experience with them, so is it liquid in there or is it gas cylinders? Because people can't turn oxygen out as a liquid, you know, like that.*

C: Yeah, I was thinking there must be something in between, you know, so it doesn't come straight out. {C}

The students once again start thinking about the possibility of oxygen becoming a liquid. Betty uses an analogy of welding cylinders to claim that it is possible for oxygen to be in liquid form in the tank as long as it can come out of it in the form of a gas. This makes Carl look for a kind of mechanism that might help oxygen transition from liquid to gas in the system. This exchange highlights how the use of real-world analogies may help students in building robust explanations together, as it helps them go beyond just the problem at hand and look at the real-world implications more holistically. The sensemaking episode continues with the students trying to understand how such a mechanism could work for the tank in question.

B: I was also thinking that if it's just pressure, basically a pressure system, then if you manage no liquid comes out, because the pressure difference is so great. {C, A}

C: Is it the pressure that causes it to change? To get it to work, is there something in there that needs to be turned? A valve.

B: A valve. Yeah, if it comes out of such a small hole there, then that's it. I don't really know, like, the temperature or anything.

C: Let's wait for more information.

A: I'd say that's it.

B: It depends.

C: I'd say it depends. If there's a valve in there, then that's it.

A: Well, if it doesn't say. Maybe there isn't one now.

B: I don't know, I feel like the valve thing is such that it sort of goes off.

The students figure out from the worksheet and the simulation that there is no valve system in the tank. This might have caused the students to stop this line of inquiry and assume that the gas does not liquefy in this situation. Next, they try to use the simulation to explore the range of pressure changes that might affect the tank. Here, they use the explorative affordance of the simulation to sustain sensemaking discussions.

A: Put it here, set it to zero and then raise it a bit.

B: You can just see that it's increasing.

C: Or should we try to adjust them so that, now we're counting, there's more temperature over there, so now we'll count it here so we're on the same level.

B: Shouldn't there be more pressure here then? Less here.

A: Yeah, we should.

C: What on earth, why did it go like that all of a sudden? We need to get it to the same place now. So, there.

Here the students maybe frustrated when the pressure does not change when they increase the temperature, since the simulation looks at volume changes and the piston is freely moving. The exploration of the simulation might have led to this uncertainty as the output does not seem to match their expectation. This seems to have pushed them out of the sensemaking frame rather than sustaining it.

B: Less, no, less pressure. I'll do it.

A: We're like, lol. Come on, let's go. Yeah.

B: Perhaps lower down.

A: Are there any different programmes we can use in this? Because the NASA thing is quite difficult to research.

B: No, this is the only thing.

This search for a program within the simulation environment may point to an answer-making frame used by the group rather than a sensemaking one in using the simulation. The uncertainty affordance of the simulation is not taken up as a point of discussion and further explanation building but the lack of specific connections between the problem and the simulation seems to have created a frustration with the simulation. This is revealed also in the written work where the students state that they would have liked for the simulation to have had a constant volume tank to better model the problem at hand.

B: It occurred to me that the programme should have a way of doing this somehow.

C: But I think the volume would be much more important, because then you can't really tell how much you can put in there without the pressure getting so high at any point that it would at least explode. {ISC, IPE, IA, C}

A: Enclosed volume, when done in a closed vessel, is the most important method.

B: That's a perfectly good idea. The fact that it doesn't change. That piston system doesn't really fit in there.

A: Well, where, um, should the oxygen be, um, sort of, like, what is that phase diagram? The one with the triple point, so you could see straight away at what pressure it turns into a gas or a liquid. {IPE}

B: Right then, that's that. But it would still be nice to know that boiling point and that sort of thing.

C: Right.

C: Is the tank safe when I'm out in extreme temperatures? How extreme are they? Right. I'll put a bit in there, just in case. It depends on how extreme they are.

A: I think this is a good question, but not enough information has been provided. This gives too broad a scope.

C: That's it. It's a shame things are like this. This is just how it is.

The students then move to resolve the discussion by noting that there is not enough information to answer the question. From the written work also, it is also clear that they would have liked to know the phase diagram to know if the oxygen would have become a liquid in the temperature ranges. Also, not knowing the exact temperature also seems to have put off the students from pursuing the problem further. Thus, the sensemaking episode has moved onto understanding what factors they needed to answer this question.

This episode highlights the use of the explorative affordance of the simulation in places to help sustain the discussion. The frustration that the uncertainty factor adds to the sensemaking may actually prevent the students from engaging in sensemaking. The expectation of the students might play a major role in whether sensemaking happens. In this episode, the students seem to approach the simulation as a way in which they can confirm their hypothesis. Thus, the sensemaking components in this episode flow more from how the worksheet is structured and the simulation often is not looked upon as a resource for sensemaking. Within the framework of sensemaking, the students engage in robust explanation building, using mechanistic reasoning as seen by the presence of higher-level codes. They also go beyond the scope of the problem when using analogies to understand if the oxygen could be in the liquid state. This may be given as evidence for the presence of structural components of sensemaking in this episode, though it is not sustained due to simulation affordances. Thus, this episode may highlight the importance of more guidance in simulation use for the students to be able to use simulations as a tool for sensemaking rather than for checking answers.

4.1.5 Episode 5 – Group 3

The next episode continues the sensemaking trajectory of Group 3. The students are now in question 3 of the worksheet discussing the effect of non-ideal gas parameters like particle mass, particle size and particle attraction on macroscopic properties like volume, pressure and temperature. The students enter the sensemaking frame when Ayden articulates the problem statement.

A: The pressure and temperature, as well as the particle mass. Now let's look at this.
C: A hypothesis about the relationship between pressure, temperature and particle mass.
A: Well, the particle mass first.
B: The pressure increases? {C}
C: Does it matter if the particles are heavy? {IPE}
B: Do they collide more slowly or more forcefully as a result? Of course. {IA, IPE, C}

The episode begins with the students discussing possibilities of changes in particle mass. They explicitly connect mass to increase in force of collisions, decrease in speed of collisions and an increase in pressure of the system due to these collisions. This assemblage of knowledge elements can be an indication of fruitful sensemaking.

A: But couldn't it be that the lighter the particle is, the faster it moves? {IPE, IA, C}
B: Yeah.
C: Doesn't that then affect the temperature and pressure? {C}

The students start discussing the effect of particle mass on speed of the particle. They explicitly chain this to its effect on temperature and pressure. Thus, the students show an awareness of how microscopic properties have an effect on macroscopic properties.

A: Well, is the particle mass determined by the protons inside it? {IOE, IPE, IE}

B: Protons and neutrons. {IE}

C: Yeah.

A: So there might be more protons there, and they might also have more electrons. {IE}

B: And it might have more neutrons. {IE} *Am I right in saying that's an atom? Well, I'm not entirely sure.* {IE}

A: What exactly is particle mass? I don't know if there's a specific mass for particles.

The students then move onto discussing what can be the factors influencing changes in particle mass. They may be trying to attack the problem by thinking about how the mass can change in the first place to see if that helps them understand any macroscopic changes. But the students do not pursue this line of inquiry further and they come back to thinking about the relationship between particle mass and collisions.

A: I was wondering, could it be that particle mass affects how hard they collide with each other? {IA, IPE}

B: If you think about small balls, for example, they hit each other. And then when there are big balls and they weigh more, they sort of bounce off each other more. {A, IA}

C: Yeah, and so when I think about size, it immediately occurs to me that the bigger they are, doesn't that sort of increase the likelihood of them colliding, because they take up more space. {IA, IPE, IOE, C}

A: But here we're only talking about mass. {IPE}

B: We're not talking about size.

C: Right, well, anyway.

A: Because if mass isn't directly proportional to particle size, then you can't really say. {IPE}

The students explicitly think if the size of the particles have any effect on mass and reject that notion. Betty also uses the analogy of big balls and smaller balls, though they find it is not relevant here since the analogy works for particle size and not mass. This analogy, though it didn't work, sets up the next analogy with reasoning different from this.

A: But then again, if the mass is such that it goes the fastest again. Will it go that way again? Well, then you think, if two smaller stones hit each other, do they collide more slowly? {A, IA, IPE} *Don't they actually go faster if they're lighter? Right, so is it just that the lighter they are, the more it sort of increases the temperature and pressure, and maybe the volume?* {C, IPE}

B: Well, but the thing is, if our first conclusion was that these factors influence each other in a way.

A: Well, they're small, but they're also light. Right. {IPE}

Ayden reuses Betty's analogy from earlier repurposing it to signify difference in mass and claims that particles with less mass go faster and uses this as evidence to argue that the lighter the mass, higher will be temperature, pressure and volume. Next, Carl wants to discuss if the effect of particle mass on temperature is only through the particles' speed or they have a more direct effect.

C: I was just wondering if they affect these directly, or if these just affect that, of course, in terms of how fast. {IA, IPE}

B: Well, I don't know.

C: I was wondering if they affect the temperature outside, or their own temperature when they're moving.

A: Yeah, yeah, let's say, the lighter they are, the faster they'll collide. {C, IPE}

B: They're gaseous precisely because they collide more, as they're lighter.

The students seem to conclude that the speed of the particles is the difference if particle mass is changed and they reaffirm their claim that the lighter the particles are, the faster they will collide. The changes in macroscopic properties are not being considered here. They link the gaseous state with higher number of particle collisions, making the connection that gases have lower particle masses. The students move on to exploring their hypothesis using the simulation.

A: The question is, does it increase?

C: I'd think it moves.

A: The temperature rises.

B: The movement increases even more. {IA, IE}

B: And it does change, but it's not quite the same as pressure, temperature or, well, volume.

C: Yeah. Constant.

A: OK, I'll move on to the next one.

The students have seen that the particle mass does not change the macroscopic properties, through the feedback from the simulation output. This causes them to move to the next question. They do not use this feedback to question their previous reasoning.

B: It's the particle size.

A: Well, doesn't that mean the same thing again, that the bigger the particles are, the more likely they are to knock out the normal ones, and that in turn affects the temperature and pressure and so on. {C, A, IPE}

C: Right.

A: What do you reckon? I was just wondering if that's exactly why, they're sort of bigger and heavier. Big balls, smaller ones.

B: But if the volume increases, even if they're bigger than these, then it's less likely they'll collide with each other if the volume increases. {IPE, IA, C}

C: Well, it affects all of them, but perhaps not in such a way that they all increase.

A: Isn't that right? Well, do they have any effect on that at all, then? But of course, if you think about it like this: these are this size, and there are bigger ones here, then of course it does have an effect.

The students use the analogy of balls again to reason that the bigger the particles are, they collide more increasing temperature and pressure. They then try to construct an explanation for how this may play out. The students turn to the idea that more collisions between particles indicates more volume. They then seem to state that other variables like pressure and temperature also increase. They next turn to the simulation to see how particle size affects volume, pressure and temperature.

B: They do collide quite often. {IA}

A: Yes, that's true, they do collide.

B: As the surface area of the particles increases, the probability of a collision will probably always increase. {IA, IOE, IPE, C}

C: I was thinking about collisions.

B: But will the temperature rise? I was wondering, if volume increases, won't the temperature sort of drop? And the pressure drop? Yeah, would it be like that? If it increases. {C}

The simulation output seems to show them that the collisions increase with increase in particle size. The representational affordance of the simulation then allows some sensemaking into why this is the case. Betty claims that the probability of collisions increase since the surface area of the particles has increased due to their greater size. She may have been using the simulation's representation of particles as evidence for this claim. The students also notice that volume increases and Betty claims that temperature and pressure should drop because of this. They then check the simulation to see if their reasoning is correct.

A: The volume increases.

C: Doesn't the volume increase? The volume increases, yes.

B: The volume increases, the pressure and temperature should decrease. It hasn't dropped.

A: No, it hasn't.

C: Volume increases.

B: That was right. P and T. They didn't increase.

A: Yeah. Right, that's that sorted.

C: Right, that's good enough.

Once again, the simulation seems to show that they were not fully correct in their reasoning. The students do not try to build an explanation for this difference and accept that they are wrong and the simulation is correct. There may be a tendency to use the simulation as a check for their answers, but not as a resource for further discussion once they are shown to be wrong in their reasoning. The students now move on to particle attraction.

B: Well, I was just thinking, again, that those particles, they don't normally have that much attraction, do they? They bump into each other now and then. {IPE, IA}

C: Yeah, true, if they clump together. {IOE}

A: Sort of.

B: Yeah, sort of, if they do pull each other towards them. {IA, IPE}

C: So they all end up together.

B: I thought that normally they don't have any kind of pull, sort of.

Betty claims that particles do not attract each other generally. Carl builds on this by arguing that if the particles attract each other, they may clump together and end up together. Carl seems to suggest that this may not happen in real life. They then turn their attention to what this might mean in terms of particle collisions.

A: It pulls; if they're about to collide, it pulls them towards it more strongly. {IA, ISC, IPE}

C: But then again, when they hit each other and go off in different directions, it sort of slows down. It stays in place and holds up. Yeah. {IA, C, IPE} *Then they might end up going their separate ways again anyway. Yeah.*

A: I was wondering, does that slow them down anyway? Well, probably, yeah. {IA}

B: The overall movement, perhaps. Yeah. Yeah, probably. Yeah, I'm sure it'll slow them down and reduce the speed. {IA, IPE}

The students seem to claim that the speed of the particles may reduce if the particles attract each other more. They argue that the speed of collisions may slow down, since they do not move as fast away from each other. They use this argument as evidence to reason that the overall movement of the particles will reduce. They then consider the effect of these microscopic changes on macroscopic properties.

C: Yeah, and then if that affects the movement and that affects the temperature and all that, then that's it. Yeah. {C, IPE, IA}

B: And I suppose the volume will decrease as well.

A: It slows down.

The students have formed a hypothesis and use the simulation to check this. They use the explorative and feedback affordances of simulation to sustain their discussion here.

C: If we change attraction in the other side.

A: So the volume decreases and the pressure...

B: Oh, the pressure probably decreases. No, wait. Don't you think so? It's going down. No, it doesn't.

A: Well, I suppose it could stay the same if the volume decreases, but then that's it. So it doesn't change at all. Right.

C: Sure, the volume can change without the pressure changing.

B: It takes up less space. But then that's exactly the point.

B: A bit less Volume. Thanks.

The students check their hypothesis and find that volume did decrease as predicted. Once again, the fact that pressure and temperature were not affected is not taken up further and they are satisfied with knowing that their hypothesis is not correct. This is also shown in their written work, where there is more reasoning in the worksheet where they are asked to hypothesise, while there is just a statement that their initial hypothesis is right or wrong for the answers when using the simulations.

This episode showcases the explorative and feedback affordances of simulations in sustaining sensemaking. The episode is rich in robust explanation building when the students are generating hypothesis. They use analogies, argue with evidence and showcase the use of mechanistic reasoning (shown through the higher-level codes present in the transcript) while understanding the effects of particle mass, size and attraction on volume pressure and temperature. The students also show that they can chain their reasoning based on the microscopic properties like speed of the particles and translate them into macroscopic variables like pressure. However, when using the simulation, the students resort to just checking the correctness of their hypothesis without further engaging with the uncertainty affordance of the simulation. This affordance is present in plenty, since the simulation output goes against their reasoning in many places, but the students do not use it to sustain sensemaking as they treat the simulation as a resource for answer checking. Thus, this episode highlights the importance of guided scaffolding within the activity to ensure students engage in sensemaking even if the simulation may offer affordances for the students.

4.1.6 Episode 6 – Group 4

The next episode is presented from the discussions of Group 4 consisting of two students (Pseudonyms: Gina (G) and Bruno (B)) as they investigate the fundamental relationships between volume, pressure, temperature, and the number of particles in gases, through question 1 from the worksheet. The episode features the use of the simulation's uncertainty affordance as an important factor in sustaining discussion. The episode begins with the students entering a sensemaking frame by attempting to define the parameters of the system and articulating the problem statement.

G: What is the volume and number of particles? And what would be the volume?

B: Temperature, pressure, that's the number of particles. Number of particles. It's not a volume in itself. Volume and pressure are inversely proportional. Because if the volume decreases, then the pressure increases. {ISC, C, IE}

G: The volume increases and the pressure decreases. Because they don't have room to move freely. Are these two pictures because if we do this second, then we'll see what the difference is. {IE, IA, C}

The students start the discussion by articulating what they know theoretically about the pressure and volume in the system. They clearly explain why pressure and volume are inversely proportional.

G: Okay, so basically we could increase the number of particles here. Should we change this one, or maybe that one? So basically what? For a larger amount of particles, large is the volume. Yeah, that's right.

B: And now that this is moving adiabatically here, that's why the pressure doesn't really increase. The pressure remains constant. Since this is where it gets more moving, that's why here this pressure parameter doesn't change. {ISC, IA, C}

Here the students use the simulation to explore the properties of the gas. They see that in the simulation, the pressure doesn't change when more particles are introduced. This means that volume increases. Bruno describes this as an adiabatic process.

G: Should we increase pressure?

B: Why don't you try it? It'll probably move this piston down then. {C, IA}

B: Yeah, look, now it's moving down. Yeah, that's right.

G: That is, the pressure of these particles increases.

B: Yeah, or the pressure in the system increases because the volume decreases. {C}

G: Yeah, that's right. Pressure increases as volume decreases. {C}

B: Yes, it is. But... And the pressure increases, or so the volume increases if the amount of matter increases. And if we keep the volume constant while increasing the amount of substance, what happens when the pressure rises? I have to write a little so that I can do this.

The students want to check what happens if they increase the pressure. They see that the piston moves down, reducing the volume. This creates confusion in Bruno, who seems to not realise that they haven't changed the number of particles but only the pressure. He seems to think that the pressure increasing is due to more particles.

G: It was almost at the same time that when the amount of substance is increased, the volume increases. Yeah, that's right.

B: If it can grow freely?

G: Yeah, that's right. It's free. Should we respond by saying that we were led to think that pressure and volume are inversely proportional?

B: Yeah, that's right.

Gina resolves this confusion by stating that the volume increased only when they added more particles and because the piston is free to move. They next move on to the problem about volume and temperature.

B: Volume and temperature.

G: I'm gonna write this.

G: Yeah, that's right. It works just fine. Volume and temperature. If you think that the volume or piston moves freely further. The temperature causes more movement? {IA, ISC, C}

B: Yeah, that's right.

G: If the pressure stays constant. Will the pressure stay the same? {ISC}

B: Yeah, that's right. If that wall moves freely, then it goes so that when molecules collide there like this. That movement is bigger than that, so basically it affects. {IE, IPE, IA, C, IOE} *If the solid piston did not move anywhere, then the pressure would increase.* {ISC, C} *The temperature would be directly proportional to the pressure. But now that it moves freely, it happens that when the pressure stays constant, it changes the volume.* {C, ISC}

B: And then you know how to think that if the gas expands like this, then it needs, it takes energy. And when you give it more heat, it gives it energy for the expansion work. {C, IA, IPE}

G: Let's write our hypotheses as they were

Here Bruno claims that when the temperature is increased it leads to more movement of the particles, leading to more collisions, leading to higher volume if the piston can move. He also explicitly connects his reasoning to an argument that if the piston can't move then pressure would increase. He then uses the representational affordance of the simulation as more evidence to indicate that the piston moves freely, and the gas expands when the temperature is increased since the heat for expansion is provided by the increase in temperature. Next, Gina wants to check the pressure change due to increase in temperature, since they hypothesise that the pressure remains constant.

G: So this is probably where we're going to raise the temperature. How much is it? Well, we'll raise it. Well, I'll click a few times and see what happens

B: The pressure stays constant because it moves freely there. {C}

G: But there's more pressure here than here.

B: It shouldn't, if that's the case. If it moves freely, then that's how it is. {ISC, IA} *But does that actually mean something about the interactions between the particles? Gas pressure or something? I mean, is the pressure of the system a different thing? And then that.*

Here Bruno encounters something which goes against his intuition. Gina notices that the value of pressure in the simulation has increased. It is unclear what this refers to since they have not changed the pressure themselves, and the simulation only shows the changes in volume. But this fact makes Bruno think again about what pressure here indicates.

G: But the thing is, temperature is increasing. The volume and pressure both cannot increase. How can they be arranged if the pressure increases? We don't really need to write about the hypothesis. {C}

B: Otherwise, it only makes sense that if this moves completely freely, then the pressure would not change. {ISC, C}

B: Is there actually a bug? Let's try that again and then add that.

G: It's like a mess. reset. This is it. Or like a start. At the starting point. When the temperature rises, the volume increases. Because if this isn't limited in any way, then it's true. Okay, good.

The issue makes the students sustain their thought process and they want to confirm their thinking again. They see the output again and Gina is satisfied with the feedback from the simulation as it shows that with temperature increase the volume increases.

B: No, but if—I mean, if we increase the pressure here, then the volume will increase as well
G: No, no, no, no. So, if you look at it the other way around, it's not that it just keeps growing and growing—it's actually the exact opposite.

B: No, but that situation would be different if we put this on the outside, external pressure. If the external pressure increases, then this volume would decrease. But was it the case now that if this pressure increases, this pressure of the system, up here it increases, imagine that you have a boiler with water and it boils. {A} *If it, if it produces, the lid could move freely in it, then the temperature would rise, the pressure would increase, then it would also increase the volume.* {IA, IPE, C, ISC}

Bruno is still confused by the fact that there was a change in pressure with the change in volume and this makes him try to reason why it was so. He seems to discount Gina's recent observation from the simulation and constructs an explanation for why pressure would also increase with increase in temperature. For this, Bruno tries to use an analogy of a water boiling vessel as evidence. He wrongly reasons that if the lid in such a vessel could move, then when the temperature increases, the pressure and volume both would rise. Gina is now confused by this line of reasoning.

G: If it moves, yes, if it moves freely. Yeah, that's right. But then again. Doesn't it move freely? Well, yeah, but what I mean is, if we...

B: Well, let's think that we increase the pressure of this with some pump, some piston, then it also increases the volume of this. {A} *If we pushed some more stuff, it would increase the volume.* {IA, IPE, C}

G: But doesn't that make it the same thing? Or that if you want to increase the pressure, then the volume cannot be increased, because then the situation is the same. {C} *Or that if you want to increase the pressure, but still that volume moves freely. I don't know. I'm totally freaked out right now.*

Bruno tries to remedy this confusion by giving another example analogy. He claims that if there is a pump connected to the system, then by increasing the pressure, by pumping more gas into the system, they can increase both the volume and the pressure. His line of reasoning misses the fact that in that case the number of particles has increased in the system. Gina expresses her original claim that if the pressure has to increase then volume cannot be increased. She also expresses frustration with the situation.

G: Now we'll see. I think I understand that, because if you increase the pressure, it doesn't work that way. Or something like that. Yes, if the volume moves freely, then the volume will increase with. {C, ISC} *It's true. Now I understand what you mean. I thought, in principle, according to the equation, then.*

B: We talked from a slightly different point of view. I mentioned that we should ask [instructor] too whether this means the system needs to be connected to an external device. {ISC}

G: Okay, now we're on the same page. That is, it is assumed that the volume will also increase when the pressure is increased. {C}

Gina has now rationalised for herself Bruno's line of reasoning. She assumes that the ideal gas equation does not apply to the situation here, since it may not be an isolated system. The students' explanation for why the simulation output was different than thought of is explicitly linked by their reasoning to the setup conditions of this system. They assume that the system is connected to an external device, which is the reason for the anomalous behaviour. But they are again challenged when they check that when the pressure is increased, the volume of the system decreases, and does not increase as they had expected the simulation to behave.

B: If it's this system, this pressure. The volume will increase.

G: So it did. Wait, wait, wait, wait. The volume decreases!

B: It's external pressure.

G: Yeah, let's talk. That is, it is as if the volume is decreasing.

B: Yes, it is. No, but that cleared things up. It's external pressure. That means external pressure.

B: If external pressure is increased, then the volume of the system decreases. {C}

G: It's external. Increasing the pressure.

B: volume is reduced.

G: Yeah, that's right. We should probably write here, however, that our hypothesis was exactly the opposite, because we thought it was about the pressure of the system.

Here the output of the simulation is clearer. The volume has decreased as the pressure increased. The students use this as evidence to reason that this pressure is external pressure. They argue that there is an internal pressure, which if increased increases the volume (equivalent to a pump).

G: volume is reduced. The idea was that as the internal pressure increases, the volume of the system increases because these move freely. It was the system. {C, IA, ISC}

B: Yeah, that's right. It was based on external pressure.

G: Yeah, that's right. Here it is. Shall we write the following? I guess that's enough.

B: Yes, it is.

The students reach a resolution that the system actually shows external pressure while initially they were reasoning about internal pressure. The inconsistency shown by the simulation (according to them) is not addressed explicitly and they only discuss why their reasoning with analogies like the boiling vessel and the pump do not fit with the system shown in the simulation. The fact that they had assumed that the system in the simulation was similar to the pump because they had seen a pressure jump in the simulation output is not addressed.

This episode shows the complex nature of a sensemaking sequence. The students use mechanistic reasoning throughout, as indicated by the higher level of codes and the use of analogies, but since their reasoning is not clear about the initial setup conditions (whether there is an external pump or not) the actual sensemaking does not clearly lead to conceptual understanding. There is a lack of clarity at the end even though the students did engage in robust explanation building. The simulation output was responsible for sustaining sensemaking discussion by throwing up an unclear outcome (increase in pressure when volume increased) though this might have been just a small glitch in the simulation rather than a feature. This unexpected outcome helped the students to come up with an explanation and the simulation representation of the piston helped provide evidence for reasoning why the pressure increased too. This is a case where the uncertainty of output from the simulation sustained sensemaking, though the direction of travel within the sensemaking episode did not lead to better conceptual understanding.

4.1.7 Episode 7 – Group 4

This episode is from the Group 4 again as they evaluate the safety of an oxygen storage tank subjected to the extreme temperature variations on Mars, through question 2 from the worksheet. The main focus of discussion within this episode is the relationship between macroscopic properties influencing tank safety and the effect of temperature and pressure on the organisation of particles, specifically when investigating whether pressurized oxygen will remain a gas or liquefy and how that transition affects the risk of a tank explosion. The students enter the sensemaking frame by rephrasing the question from the worksheet. They start their explanation building by arguing that with increasing temperature the particles move around more causing the pressure to increase.

G: Okay, make a hypothesis. Is the tank safe in the extreme warmth of Mars if it is full? Yeah, that's right. Full, huh? I don't know. Well, it must be in the wider temperature range. It's getting warmer, and then they start moving around. {IA, ISC, IPE}

B: Yeah, yeah, yeah. It takes a lot of space. That's when the pressure grows, if it ruins the tanks. {C, IOE}

G: Yeah, that's right. Let's see what else is going on.

B: But then, if that if it liquefies under higher pressure, its volume will decrease quite drastically. We have a gas tank, that's how it's gonna be. It's liquid, isn't it? It's only when the pressure drops that the fuel starts to vaporize in the tank, and that's when it turns into gas. {IOE, IA, IPE, C}

Bruno seems to be thinking that the gas may be stored under pressure in the tank, which may have liquefied it. He argues that if this is the case then the volume would be very low. He also states that the liquid oxygen will turn to gas only when the pressure is low.

G: But should we assume from this problem that we're gas molecules the whole time? If we're talking about minus 100 here, then it says that the gas molecules inside the container.

B: And so it is.

G: I think it can be assumed that it is now gas all the time. Okay, okay. Or I don't know, but somehow, since we haven't talked about anything like liquid now.

B: Is it just we saw that as the temperature increases, the volume also increases, so there should be a gas container. {C}

G: The volume increases. Yeah, that's why it needs to grow so that the pressure doesn't get too high. And then, if it's full of oxygen. That's quite a lot of oxygen. {C, IPE}

B: So the situation is that it turns into a liquid. But on the other hand, let's look at liquid oxygen. It's really cold and under high pressure. But if you have a tank of liquid oxygen and it reaches room temperature or zero degrees, the tank would explode. {C, IOE}

In this exchange, Gina and Bruno build off their ideas on liquefaction together, using the worksheet as a resource to aid in understanding the real-world situation of the problem. Gina seems to try to recollect if oxygen becomes a liquid at a temperature of -100° C, and uses the worksheet as evidence to claim that it will still be gaseous. Bruno also seems to agree, since in their exploration of the simulation they found that the volume increases with temperature, which is relevant for gases more than liquids. Bruno reasons that if the tank is filled with oxygen as a liquid and then the temperature is allowed to increase to 0° C, the tank would explode. Here we see the critique and collaboration between Gina and Bruno as they try to understand the possible state of oxygen within the tank. They use evidence from prior knowledge, their exploration of the simulation as well as the details from the worksheet to reason to a feasible explanation.

G: I bet it's here. Or I'd assume that when it's not mentioned here that it's missing liquid anywhere, when it's increasing, it's just in that temperature. But that's a good point, that I can't answer from there.

B: The warmer gas pressure is quite high. Yeah, that's right. {C}

G: It doesn't have room either, but doesn't it need more space? But that's right. Yeah, let's go.

B: But then, of course, that's the problem. The particles collide, the pressure increases. And that pressure, since it's inversely proportional, kind of gets the volume stuck. That's how it is, of course. Pressure. {IPE, IA, C}

Here, the students use their understanding of particle behaviour to indicate that as temperature increases, the particles collide which increases the pressure, since the volume is constant in the tank. They now seem to have constructed the model of the relationship between increasing temperature and increasing pressure, mediated through increased particle collisions and the constricted volume of the tank.

G: But it can be said that if it is full of oxygen, as it says here, then if it is full of oxygen, then when the temperature increases, the pressure may be too high, then it may explode. Then, go ahead, like this. Full or full. Full of oxygen. And the temperature is. And the temperature's rising. Or increasing. With the temperature rising. {C, IPE}

B: It's increasing. It's growing up. And then this pressure would remain high.

G: Yeah, that's right. That's it. I should mention that if the tank is full at minus 100 degrees, even if you fill it with oxygen at minus 100 degrees, it won't work, and then if you take it to a warmer temperature, it cannot expand at all. Or rather, basically, it should not be filled when it's cold. {C}

B: It should be filled here warmer. Yeah, that's right.

G: Should it be written that, in principle, the container should be filled in a warm place? {C}

Gina again uses the description of the problem from the worksheet to claim that since the tank is full of oxygen, the tank may explode it the pressure increases. Bruno agrees with it. Gina uses her claim to reason that if the tank is filled at the lower end of the temperature range, the pressure increase will be too much for the tank to withstand, and so the tank should be filled when the temperature is at the higher end of the expected range. This idea of identifying the initial setup conditions, beyond what is provided in the problem is an example of the rich explanation building which has happened in this episode where the students have constructed and critiqued their arguments and supported their claims with evidence and explicit reasoning to connect the two.

G: But is the tank safe? Extremely difficult if it's full of oxygen.

B: It's in the explanation. It's worth mentioning what the situation is with the liquids here. Here it is. Well, that's not a bad situation either. If it's in liquid form, the temperature rises. Let's see about that.

G: Yeah, that's right. Is that our assumption? Well, that's right. Was everything ready?

B: Should I tell you again that if the container is filled with liquid, then the pressure would probably not be enough to keep it liquid. At that temperature. {C, ISC, IPE}

The students then try to think of the possibility when the oxygen is liquid. Bruno seems to argue that even if the tank was filled with liquid oxygen, the pressure might not be enough to keep it liquid, with the temperature increase

G: I don't think there's anything liquid about that oxygen. You put it there, but I'm not really sure about it. I don't really know how liquid oxygen behaves or how it compares to gas.

B: Well, liquid volume is a fraction of gas volume. Consider how much water you take in milliliters and how much it amounts to in steam. {A, C}

G: It's true. It takes up the whole space.

B: It's kind of the critical point. So basically, the higher the temperature, the less you can increase the pressure by adding more liquid. I don't know {C, IPE}

G: The substance expands. Increasing, however, depends on nothing. I don't fully understand. I don't know. I do have something, though.

B: Let's say we have a propane tank. It's liquid in there, isn't it? In the campsite, in the woods, you have such a propane tank. Shake it, and it is a liquid. There's a lot of pressure in there, and it keeps it liquid in there. But then, when you open the valve like this, it goes into the camping stove, and it turns into gas right away. As gas, it takes up a lot more space. That one tank probably holds the whole class. {A, C, IPE, IOE}

The students try to reason further about the possibility of liquid oxygen. Bruno uses the analogy of water and steam to try to explain how liquid oxygen and gaseous oxygen may behave when

Gina says she doesn't "*really know how liquid oxygen behaves or how it compares to gas"*. Next, Bruno uses another analogy, this time of a propane tank, to explain how liquid oxygen may be present in the tank. He tries to show Gina how the liquid can turn back into gas when needed, and how the volume of the liquid changes when it turns into gas. Gina still doesn't fully understand but the students look next to test their hypotheses by looking at the simulation.

G: I don't know, but are we testing? Let's take a look. So is it here now? Here it is. Okay, so. Well, let's reset. No, now the pressure is rising. The temperature is being increased. Yeah, those go faster over there. {IA, IPE, IE} *Then there's that hundred-point difference.*

B: Yes, or if this temperature was lowered here, then this volume will also decrease. The pressure is still there. So if this wall moves like this, then their pressure is same but the volume is different. Right, that's it. It's a big one, isn't it? That is volume. That's how I see it. {C}

G: It's like, do we have to try to make that pressure the same now? Or like, that pressure isn't the same now, is it?

B: The volume should remain same.

G: There's nothing else you can do here.

B: Should we just stop it altogether?

G: No, I just thought that other people had thought the same thing. But then, you just have to decide to do it. Or figure it out some other way.

Here the students seem to be frustrated at the fact that they cannot get the volume to remain constant in the simulation. Bruno notices that because the piston is movable, the pressure remains constant even when there is more temperature, but the volume increases, which is not similar to the situation of the oxygen tank. When Gina notices that it may not be possible to keep volume constant, Bruno seems to think that the simulation is not helping them. This uncertainty, though, sustains the discussion as Gina wants to see if they can "*figure it out some other way"*. Thus, the uncertainty affordance of the simulation seems to sustain sensemaking in this case.

B: No, there's pressure here. The pressure is the same, because this isn't the same situation. The wall is moving. {ISC}

G: There, now it's the same as mine. But. That's what this looks like, of course.

B: After all, that's the whole point you shouldn't leave something like a can of spray paint burning in the yard. It's exactly the same. {A}

G: But then it'll get warm. That's where we've been thinking.

B: Well but these also are warming up. That's 100 degrees below zero.

G: It's true. It's true. How can we say that.

B: Not me, either. Now we need to calculate what pressure might occur there with that temperature change. I think this is kind of... impossible. It does stay the same, because this volume can change. It can. But in the tank, it's a big deal. {ISC, C}

They continue trying to see if there is a way to make pressure constant, which they are not able to as the piston is moving. Bruno offers another analogy of a spray can left in the heat to emphasise their previous reasoning that the tank may explode. Bruno finally indicates that it may be impossible to directly see the effects of temperature on pressure in this simulation, but makes a point that the changing temperature will be of importance in the tank situation since the volume cannot change.

G: Yeah, that's right.

B: This is pretty straightforward, but we can't really give any specific examples for that task right now.

B: I looked at where this was.

B: Now we need specs that what kind of pressure that tank can withstand. Then we can calculate it based on the change in the temperature. But we can't give a decision on this basis. We need specs. If the tank can withstand. {C, ISC}

G: So what are we going to say? Oh, man. Seriously, this area is a pain

B: It's really tough.

The students reach a resolution to this episode by stating that without knowing the "*specs*" of the tank they cannot conclude if it can withstand the pressure. In their written work they also indicate that the tank may not withstand the high pressure. This may be due to their reasoning through the use of analogies like the spray can in heat, which they see as evidence for their claim that the pressure may be high, especially if the tank was filled at lower temperatures.

This episode highlights the explorative and uncertainty affordances of the simulation that helps sustain sensemaking in the students. The students also reason mechanistically, as seen by the presence of higher-level codes. The use of reasoning through analogies, particulate mechanisms, and collaborative construction of explanations provide evidence that the students engaged with the sensemaking epistemic form involving robust explanation building. The episode also highlighted the rich back and forth construction of explanations, using a variety of resources such as the simulation, worksheet and prior knowledge and the use of real-world analogies helped the students move beyond the problem statement to try to figure out if the oxygen is in a liquid state. Such moves reinforce the notion the students were engaged in sensemaking and were trying to understand the situation carefully rather than trying to come up with a solution to the problem quickly.

4.1.8 Episode 8 – Group 5

Next, we come to the sensemaking process of Group 5 consisting of two students (Pseudonyms: Teemu (T) and Emma (E)) as they evaluate whether an oxygen storage tank remains safe under the fluctuating temperatures of Mars, through question 2 of the worksheet. The main focus of this episode is the use of real-world analogies to make an engineering safety judgment in the absence of specific technical specifications. The episode starts with the students entering the sensemaking frame by articulating the problem statement from the worksheet. They start discussing pressure fluctuations as a possible cause for failure for the tank.

T: Is the tank safe at the extreme temperature of Mars if it is full? Could be. Could be. It's zero, but it's not big. It's a little bit. Not yet.

E: What do you mean, like. The pressure, too. Full-screen option. So the fact that, yeah, that temperature fluctuates, which is why then that pressure fluctuates there. That is, their temperature varies there. {C}

T: Yeah. Roughly, if it's now 300 and 150, it's still far away. And then the pressure would be even lower. So the pressure would be halved. {ISC, C}

E: Like I don't know what else to do here.

T: And it's kind of a lot of pressure over there. Is it safe? Is it safe? It has to be. Or maybe the oxygen tank will burst open. Safe in that sense. But I've been thinking that our temperature is half and the pressure is roughly halved. Is that how it can withstand half the pressure variation? It's a container. {IA, ISC}

They use the feedback affordance of the simulation to see what happens when the temperature is halved. They see that the pressure would be lower if the temperature is lower. Teemu seems to be thinking that if the tank can withstand half the pressure variation it can be safe. He seems to have made this reasoning based on the fact that the higher range of temperature they are checking (300 K) seems to be double that of the lower end of the range (150 K). Thus, he seems to reason that the pressure will vary similarly since it is directly proportional to temperature.

E: Yeah, but I was just thinking about how quickly the pressure changes. What do you know? Probably not if they know. Really fast those pressure fluctuations. It is also different from the fact that if the pressure changes slowly. I don't know what time Mars is, how fast it goes around its sun. But what if the pressure fluctuates? {IA, IPE, C}

T: And it's just its axis around rotating day and night variation.

E: Like if it's too much, I'm sure it will, summer lasts 4 months.

T: Yeah, that's right. The other thing is that it depends on the container. {ISC}

E: Well, others I don't know, you've told me what's in the container. It's all the way. What material? Not if it is. Is the tank safe? I don't know. I don't know, though.

The students consider other factors such as the time taken for night and day in Mars, the length of seasons and the material of the container. This assemblage of knowledge indicates an entry into explanation building as they can use prior knowledge as resources and evidence for claims while building scientific explanations. The range of ideas they consider may also serve as evidence to state that the students are sensemaking rather than answer-making. They seem to want to understand the real-life implications of the situation rather than trying to answer a problem in a classroom.

T: If it can withstand double pressure variation, then it is safe. If not, it's difficult. {C}

E: Is there a double pressure variation? I don't know about the pressure, I'm not very good. What if there is double pressure, is that a big deal?

T: Well, I don't know—it probably isn't that much. If you think about how much pressure there is in tires, and how much pressure is in a bicycle tire, around 3 atm, it wouldn't be that bad if it were halved. It's a little more typical. {C, A}

E: Let's just say it's safe. The alloy is safe as double pressure variation is not that large. {C}

T: Yeah, yeah, yeah.

The students try to reason if the pressure variation they calculated earlier may cause failure of the tank. Teemu gives an analogy of bicycle tires. He claims that the pressure in a bicycle tire is around 3 atm and if it is halved, it doesn't cause too much damage. The analogy seems to be going the other way round compared to their previous discussion. In their previous discussion, they seemed to be discussing that the tank may explode since the pressure increases, whereas in the analogy Teemu talks of a situation where the pressure decreases. Emma seems to think that the tank could withstand such a variation based on the evidence provided by Teemu.

T: I mean, if it can withstand the upper and lower limits, and it's such a huge pressure variation now, then it's just fine. {IPE, C}

E: Yeah, that's right. It'll take a while, because. At least the interval, because the pressure varies, it's big. Time interval, pressure variation. The pressure to fluctuate, like, what is it? Large? {ISC}

T: All right, there it is.

E: Storage tank. Storage tank, for possible use. So you know it's full for so long. Will it stay intact until it has to be used?

T: Yeah, that's not enough with this information.

They come back to their discussion on the time it takes for the pressure to fluctuate. They may have an idea that if the variation is faster, it may lead to failure of the tank. Since the worksheet does not provide them with a timeline of the temperature fluctuations, they may have thought that the information is not enough to answer the question. They next try to use the simulation again to see if they can confirm their hypothesis about the pressure variation the tank may have to withstand.

E: Test the hypothesis with simulation. That's reset. Is the tank safe at extreme temperatures on Mars? So, if we set our temperature now. Is zero like, is zero our other extreme and minus a hundred brought the other extreme?

T: Here you go, yeah.

E: What annoys me in this simulation is that can I know if we have the volume constant here, then why can't I test it for the fact that the volume constant is constant? Why is that piston moving here? What's going on here?

Emma seems to show frustration at the fact that they cannot maintain a constant volume in the simulation. Emma notices that because the piston is movable, the pressure remains constant even when there is more temperature, but the volume increases, which is not similar to the situation of the oxygen tank. This uncertainty, afforded by the fact that the model of the simulation does not match exactly with the world of the problem, causes them to try to find out a different way around this problem, sustaining sensemaking.

T: What's going on here? What's next?

E: But then we can make pressure go up right away.

T: And then if we go change that pressure.

E: It affects the volume, doesn't it? If our pressure is increasing, so is our volume. Yes, the volume. So our pressure decreases now, volume increases. I'm going to put zero temperament here. {IPE, C}

T: But now our pressure is lots.

E: So, isn't that pressure going down because that volume is going to increase? {IPE, C}

The students seem to try to use the explorative affordance of the simulation to circumvent the fact that the volume does not remain constant in the simulation. They try to see how volume changes when the pressure is halved. They see that the volume increases with decreasing pressure. They next try to see how the simulation behaves when there is temperature variation. They notice that when the temperature drops the volume drops too.

T: And we wouldn't want our pressure to be halved if we wanted the volume to be the same, so now we would keep that pressure just a little bit. Well, now that we've constant volume, now we've got something like that. So now it was halved to the temperature, and then the pressure was halved, and now we should have the same volume. {C, IPE, IA}

E: No, it's not.

T: But that's not quite the case. The rest of this was just like I said, we don't quite hit our ideal gas. It's not working. That pressure should go down as it does. {IPE}

The students try to see if the volume is the same in case temperature is halved and, in the case where pressure was halved. They unexpectedly find that this is not exactly the case. They seem to have found a discrepancy in the simulation output. This uncertainty leads to further explanation building, where the students try to figure out why the simulation output was different from their expectation.

E: But it is non-ideal. But I don't know how I can tell if it's safe to keep. I mean, like. How am I supposed to decide with the information I have?

T: Well, maybe.

E: But I'm just confused about this piston movement now, because I just wanted to see it so that the piston wouldn't move. {ISC}

T: Of course, it's not going to get any better.

E: Yeah, but like, if I could test it so that I could see those gas particles and how they react if the piston were in place. {ISC, IA, IPE}

T: Yeah, that's right.

The students claim that the discrepancy in the simulation maybe because the gas is non-ideal. This makes them feel that the information from the simulation is not enough to answer the question. Now, the fact that they cannot check the pressure variation at constant volume makes them frustrated again, as their method of trying to check gave an unexpected result.

E: Because then it would help to perceive more of the movement of the particles, if those pistons were same. Can I get that exercise, if anything else? {IPE, IA}

T: This is a nonideal gas. Well, we do now. No, we have now. We've cut the temperature by half, haven't we? And now we have the pressure halved. Yeah, and now our volume is pretty close to the same. Now I'm just waiting for this. So, again, if it is free enough for the tank, then you should like it there. {ISC, C}

E: The temperature was halved. And half the pressure. So it has a volume of constant.

T: So it is safe.

They check the simulation again and see that the volume is close enough to equal when the pressure is halved and when the temperature is halved. This makes Teemu say that since the gas may be non-ideal the volume is close enough to be considered the same. This gives them confidence in their conclusion. In their written work, they reason that when temperature is halved and pressure is halved the volume is the same value as when temperature is doubled and pressure is doubled. Thus, it shows that double temperature variation causes double the pressure. The students end this sensemaking episode by using this as evidence to claim that the tank will be safe as they have argued earlier that a doubling of pressure is probably safe, using the analogy of the bicycle tire.

This episode shows how the uncertainty and the explorative affordances of simulation can sustain sensemaking. This is especially noticed when the students try to use the fact that the simulation environment is not the same as the one they are trying to model to solve the problem. This mismatch affords them the space to creatively use the simulation to see how much the pressure varies with temperature. The students use analogy and prior knowledge as resources for constructing mechanistic explanations, as evidenced by the presence of higher-level codes. The consideration of diverse factors like the length of the day or seasons in Mars as well as the material of the tank may show the sensemaking epistemic form, as it seems that the real-world effects of the environment were being considered apart from the information given directly in the worksheet. It may be the case that the problem statement having lesser direct information about temperature and material may have helped the students in trying to understand the problem as a real-world situation they should try to understand rather than as a problem for which a quick answer needed to be found.

4.1.9 Episode 9 – Group 5

Finally, the last episode in this analysis follows the discussion of Group 5 students again as this time, they go into looking at a storage system for methane (CH_4) on Mars as part of question 4 from the worksheet. The episode is characterized by interplay between theoretical chemistry knowledge, real-world analogies, and mechanistic reasoning regarding molecular mass and pressure. The students enter into the sensemaking frame by discussing the question and wondering if 'large amount of methane' in the problem is relevant.

E: Imagine now that you are designing a tank to store large quantities of methane as fuel on Mars. Could this be done using the same storage tank as oxygen tank, or would a different tank be needed? Explain the reasoning? A lot of methane is stored

T: Is the idea here that if there are large amounts of methane there, and if it weren't the case that we'd just use half of it.

T: This is a completely different size for methane and oxygen molecules. {IPE} *I give two oxygen atoms, but then hydrogen is produced from this—does it take up a lot of space? In a diagram like this, it does, but does it really?* {IOE}

E: Isn't that a tetrahedron, three as a base and one? {IOE}

The students discuss if the size of the particles, have any bearing on the issue at hand. As they have already seen the effect of particle size on volume from the previous question, from the worksheet, it is possible that the group is looking at this possible connection due to the way the worksheet scaffolds the inquiry process. Also, by explicitly stating the way in which size of the particles is different, they are already setting up a comparison using the explorative affordance of the simulation. If they can conclude that methane molecule is, in fact, larger than an oxygen molecule then they could use that fact as the comparison point in the simulation.

E: Minus 100 and zero. Would oxygen be a liquid at - 100?

T: I'm saying it's going to be about -190, it's going to be just that.

E: So they're both gas all the time.

T: I don't think I'm gonna do this. Would it even get in liquid form?

The students again discuss if methane would become a liquid, a point they had already considered for the oxygen tank. This frustrates Teemu, since he had already wanted the data to be given in the problem. The frustration, but is turned productive by sustained discussion by Emma, who tries to figure out the unknown by using real-life experiences.

E: Where is it stored here? Is it stored as liquid on Earth?

T: Sure, there's a use for liquids here, since there's natural gas with methane. The gas is piped directly from the drilling site as liquids. Then it's transported via pipelines from Russia, Germany, and so on. Well, let's face it, if we make it liquid, and then we won't have any problems.

The idea that natural gas is piped as liquids, which is factually incorrect, seems to make Teemu sure that it might be a liquid in the temperature ranges in the problem. Emma further probes at this by trying to see how they can check this using the simulation.

E: But is it heavier? If we were wondering what we had here. What did we have with all the attraction and mass?

T: Well, that's probably lighter. {IPE}

E: CH4, or?

T: Yeah, that's right. Let's see if the hydrogen mass is 1 and the other is 12. That's 16 and that's it?

E: So that's 32 for oxygen and that's 16 methane. It's somewhat lighter. {IE} *Can you see that? Check, is that something you can do now? It's half as light as that. We can check mass and attraction.* {IPE}

By identifying that methane has a particle mass half as much as oxygen, Emma has found a way in which the simulation can be used to explore their thinking. If the attraction is higher for lower particle mass, then it might feasibly form liquids easier than oxygen which might make Teemu’s assertion that it will be liquid more feasible. Thus, the explorative affordance of the simulation has helped Emma sustain sensemaking in this case.

E: *So when they are more attractive, then the volume decreases. But if our volume should remain the same, then what would our temperature be, what would change?* {ISC} *That stays the same. If our temperature drops, then our pressure should drop.* {C}

T: The reduction in particle attraction now simply makes pressure that decreases. {IPE, C} *Now we need to get this system working again. So, the pressure was the problem here. It may be that we need something even stronger.*

Looking at the simulation output, Emma figures that volume decreases if the particles are more attractive, but it is unclear if the relationship with mass and attraction was also checked. Teemu seems to have reasoned that the decrease in particle attraction means that the pressure will be lower in the case of methane, making the variations in pressure in the tank wider. He uses the simulation output as evidence for this claim. According to him, this may lead to the tank having to withstand a wider range of pressures than it is rated for currently.

E: So, does the pressure vary even though the volume remains the same?

B: Yeah, that's right. So its pressure decreases more than it does with oxygen, so you have to be more stronger. {C}*. Or, if the volume remains constant, then the pressure changes more than the oxygen* {ISC, C}

G: The pressure changes in CH4. It's more than oxygen.

B: So it has to be stronger. With this information.

G: Stronger than oxygen, yes.

The students come to a resolution that the tank has to be stronger for methane than it is for oxygen. Their line of thought is expanded further in their written work, where they provide evidence and reasons to their claim. They write that since O_2 and CH_4 are molecules of roughly the same size and CH_4 is lighter than O_2, there are no attractive forces. This lack of attractive forces leads to wider pressure changes in methane than in oxygen leading to the requirement of a stronger tank.

In the explanation building phase of this episode the students again showcase many of the characteristics of scientific explanations and mechanistic reasoning. Specifically, they identified that the way the entities (atoms) are organised can be used to reason about what will happen in the future. This was done with reference to the size of the particle being affected by the way in which hydrogen atoms surround the carbon atom. The use of real world experience (natural gas pipelines) indicates certain amount of engaging with sensemaking. Also, looking at the codes of mechanistic reasoning in the transcripts above, higher level codes such as chaining, identifying organisation of entities and identifying properties of entities are present through the explanation building phase. This builds confidence that the students engage in mechanistic reasoning and sensemaking.

This episode highlights the explorative affordance of simulations in sensemaking. The way in which Emma suggests an experimental view on whether methane can be liquified easier than oxygen showcases the explorative affordance of simulation, along with the immediate feedback that the simulation provides. The simulation helped them move into an orientation of comparisons, side by side initially for particle size, as well as later when reasoning about the effect of particle attraction. This experimental orientation is important as a skill within inquiry and as such the connections between sensemaking in chemistry and experimentation is seen in this episode. On the other hand, their conclusion is uncertain since the reasoning behind it is not discussed explicitly. This jump in reasoning also highlights the fact that though the structural features of sensemaking and characteristics of mechanistic reasoning are present, it might not lead to a fully correct scientific argumentation. Thus, this episode also highlights the difference between sensemaking and conceptual understanding.

5 Discussion

The purpose of this study was to uncover the processes involved in student sensemaking using interactive computer simulations in an inquiry-based lesson in chemistry. This was done by describing how students discuss and work to solve real-world based problems through interactions with computer simulations while analysing the affordances simulations offered the students in this sensemaking process. This chapter discusses the results of the study to highlight the similarities and differences within the trajectory of each sensemaking episode described, offering some reflections on how these results fit within the broader sensemaking literature within education. This chapter also discusses how students used the affordances offered by simulations within the sensemaking episodes highlighted while detailing some of the pedagogical implications of the results that seem to be relevant for educators, simulation designers and curriculum developers.

The results showed that the students engaged in the sensemaking epistemic form multiple times throughout the sessions. Some similarities can be seen in the trajectory of student sensemaking and the moves used by the students within the sensemaking epistemic game. Some of the main similarities in student moves in the episodes were the robust explanation building with the fluent use of mechanistic reasoning, the use of simulations as a resource for reasoning, the use of scientific theories and concepts as resources for explanation building, use of real-world information through prior experiences, the use of analogies and analogical thinking and the use of simulation output as fact and a final authority. This finding supports Odden and Russ' (2018) analysis of student moves in the context of sensemaking, where they find a similar set of moves used by students in their sensemaking. In the next sections, I will discuss each of the above with examples from the sensemaking episodes while drawing connections to literature, to situate the results within a particular context and, also, broadly within science education research.

One main finding was that students typically engaged in robust explanation building with the fluent use of mechanistic reasoning within their explanation building. This is seen in the analysis of the students' written work as well. In Episode 1 by group 1, Andrea constructs her explanation of why she feels that more particle attraction leads to lower volume of the gas. She uses the evidence from the simulation and previous reasoning that with higher particle attraction the particles clump together. She then builds on this further by reasoning that the volume of the gas is affected because fewer particles collide with the piston and more particles collide with each other. She then explicitly combines the evidence and claims to reason that if the attraction force increases, this will lead to lower volume. In episode 2 by group 2, Cia claims that the pressure of the gas increases when the volume decreases. She uses the scientific formula for calculating pressure ($P = F/A$) as a resource to connect to the representation from the simulation that shows that the area in which the particles operate reduces when the volume decreases. She reasons that since there is no change in the temperature, the forces remain the same, in a smaller area the pressure increases. Cia seems to be fluent in connecting the microscopic realities of particles to macroscopic behaviour characteristic of mechanistic reasoning. This supports the finding from Sirnoorkar and Laverty (2023) where the authors assert that tasks that cue students to generate mechanistic explanations or unpack the underlying mechanism of a real-world phenomenon by coordinating multiple representations can generate sensemaking.

The students also engaged in collaborative critique to build their explanations together. In episode 4 by group 3, Betty claims that if volume of the oxygen storage tank stays the same, then the temperature variations in Mars will only affect the pressure. Ayden agrees with Betty and builds on her statement by adding that if the pressure builds up too much it might force the oxygen into a space smaller than what it needs, which may lead to the failure of the tank. Carl critiques their line of reasoning by stating that since the temperature is really low the pressure may be too low and there may be a negative effect which can cause the tank to collapse inward. This critique causes the students to continue building their explanation by looking at other facts such as the temperature at which the tank was filled, whether the oxygen may liquefy and the effect of the amount of oxygen actually present at the time of filling. In episode 7 by group 4, Gina and Bruno build from each other's ideas using the facts from the worksheet as a resource along with the understanding gained through the exploration of the simulation, to discuss the possibility of oxygen liquefying in the tank. Initially Bruno uses his prior knowledge of similar storage systems to claim that the oxygen may be in a liquid state. Gina tries to critique this view by using the worksheet as evidence where it is given that oxygen gas is stored in the tank. She may also use her knowledge of the boiling point of oxygen to identify that – 100 °C is not enough to convert oxygen into a liquid. They use this collaborative construction of knowledge to reason that the tank may probably explode if the temperature reaches 0 °C since the gas may expand too much. In episode 8 by group 5, Teemu uses his understanding of bike tires to state that a double variation in pressure is not too drastic for a tank. Emma then tries to understand if the time taken in Mars for attaining this variation due to temperature extremes has any effect on their reasoning. In the end, she agrees with Teemu that there is not enough information about time variation to check that part of their explanation and that probably the tank will be safe similar to the tire. Thus, using collaboration they reach a conclusion about the effect of pressure on the tank.

The discussion above demonstrates that robust explanation building with mechanistic reasoning was seen across groups and across many different questions. This indicates that the students were used to explanation building in their course and the inquiry and problem-based worksheet was familiar enough for them to be unconstrained in their deliberation. This may also indicate that the students were generally confident with their understanding of how the movement and properties of particles at the microscopic level transferred to the changes in their macroscopic particles. In most cases, the students used the changes regarding particle collisions as the mechanism to explain volume and pressure changes while using the speed of movement to explain temperature changes. Thus, representational competence between microscopic representations and their macroscopic properties seems to be developed in the participants of this study.

From the results, we also see that the students used multiple scientific theories from prior knowledge as resources to aid their sensemaking. For example, in the sensemaking episode 3 by group 2, Aino uses the kinetic theory of heat as a resource to state that the kinetic energy of the particles is related to the temperature of the gas. Thes students are trying to see how non-ideal parameters such as particle mass influence macroscopic gas properties. Further in the episode, Birgitta uses Aino's statement as evidence to further build on their explanation of how particle mass affects the movement of the particles. She reasons that if the energy in the system is constant, then if the particles have more mass, then the particles will move slower, which may lead to lowering of temperature. In this episode, we see the students make connections between particle movement, kinetic energy and ideal gas laws while engaged in trying to figure out the problem. Similarly, in episode 9 by group 5, the students use their prior knowledge about molecular masses and liquefaction to see if methane being lighter than oxygen has any effect on if the storage tank can be used for storing methane. In this episode, Emma tries to reason if methane is easier to liquefy than oxygen by thinking about the effect of particle mass and size on particle attraction. Teemu also uses his knowledge of natural gas pipelines as evidence to suggest that methane can be liquefied easier than oxygen. These results demonstrated the findings from Ha, Park, et al. (2024) where student explored multiple resources in their sensemaking trajectory to develop plausible explanations through evaluating and revising initial ideas.

In many episodes, students used the ideal gas law as a resource for thinking about the relationship between volume, temperature and pressure of the gas. In episode 4 by group 3, while trying to see how the temperature variation affects the oxygen storage tank, Betty claims that as the temperature increases pressure will increase. Earlier she also claims that if the oxygen liquefies, this will negatively affect the pressure causing the tank to collapse inwards due to the vacuum created. The group explicitly uses the ideal gas law then to reason that since the volume of the tank is constant, the temperature variations will affect only pressure and that is what they should be focussing on. In episode 6 of group 4, the students start their sensemaking episode by explicitly articulating the connections between pressure and volume as per the ideal gas law. Gina states that pressure increases as volume decreases. They then use the knowledge of the system and state that since the piston moves, volume can change indicating that as temperature increases, pressure will remain constant. In episode 8 by group 5, Teemu claims that if the temperature varies in the tank by half, then the pressure also will fluctuate by half since the volume is constant. He uses this as evidence to claim that the tank may remain safe. These results are consistent with findings from previous research in the resources framework, where students use the ideal gas law as a resource when dealing with more advanced concepts in fluid dynamics (Young & Meredith, 2017).

It was also found that different questions from the worksheet prompted students to use different resources in their sensemaking. One important finding was that in episodes centred on real-world problems such as checking if the oxygen storage tank is safe under the temperature variations in Mars (episodes 4,7 and 8) or the problem about checking if the same tank can hold methane instead of oxygen (episode 9), the students typically used additional features of the real world going beyond what is provided in the problem description, than in questions that did not use real-world contexts. For example, in episode 4 by group 3, the students start off their sensemaking by wondering if oxygen could liquefy under the temperature conditions in Mars. This was not a fact that was prompted in the worksheet. Episode 7 by group 4 and, as seen previously, episode 9 by group 5 also include discussions about whether the gas will liquefy. In episode 4, Betty uses the analogy of a welding cylinder to explain why the oxygen in the tank may be in liquid form. Carl even tries to check if the tank system may have a valve that can be used to turn the liquid into a gas for its use. In Episode 7, Bruno and Gina try to reason about how the tank may fail by claiming that if the tank was full of oxygen, as indicated by the problem statement, then the tank may explode if the oxygen was not filled in when the tank is warmer. In this episode, Bruno tries to build an explanation around liquid oxygen and its effect on the problem by using an analogy by equating the tank in the problem to a propane tank used as fuel in camping stoves. In Episode 8 by group 5, the students try to see if the length of night and day or the length of seasons have any impact on the time it takes for the temperature to fluctuate. They try to use their judgement about the timeframe as evidence to see if the tank will fail or not. Since the time element is not mentioned in the problem, it seems to have been prompted by the real-life context in which the problem was situated in.

As seen above, a feature of sensemaking related to problems with a concrete real-world context was the use of analogies by the students. Apart from the analogy of the propane tank discussed above, Bruno uses another analogy of a spray paint can left in the sun to illustrate his reasoning that the tank may explode in episode 7. Earlier, he had used another analogy of water and steam to try to explain the increase in volume when liquid changes to gas. In episode 6, Bruno uses an analogy of water boiling in a vessel with a lid to try to explain his incorrect reasoning around how pressure and volume can increase together in a system. In this episode he uses another analogy of the pump to try to explain his view to Gina again. In episode 8, Teemu gives an analogy of a bicycle tire to explain why he thinks the pressure variation is not as bad as expected and so why the tank will not fail. In episode 9, he gives an analogy of natural gas being transported in pipelines to explain why he thinks methane may be easier to convert into liquid, which is incorrect since natural gas pipelines generally transport gas and not liquid.

From the discussion above it is seen that students use analogies in their sensemaking journeys in two ways. Firstly, they use it as a resource for explanation building through which they try to explain target phenomenon. For example, Bruno uses the analogy of propane tank to explain to Gina how the oxygen in the tank maybe in the liquid form in episode 7. Betty's use of the analogy of welding cylinders, Bruno's analogy of water and steam and his analogy of the pump and the boiling vessel with a lid all point towards the same use of analogies as resources for collaboration, where one student is trying to explain a target phenomenon using an analogy to make the explanation accessible to the other person. But, the spray paint can analogy is used by Bruno in episode 7 as evidence to his claim that the tank will fail due to the temperature variations. Therefore, students also use analogies as clinching evidence to support a previous claim. Similarly, Teemu uses his analogy of natural gas pipelines in episode 9 as evidence to argue that methane is easier to liquefy than oxygen. Thus, analogies were used either as resources for reasoning within collaborative construction of explanations or as clinching evidence presented to support a claim.

The discussion above about the use of different scientific and informal sources of prior knowledge as resources for sensemaking seems to echo the notion of establishing hybrid spaces from Chen (2025), where it is seen that students require a melding of commonsense real-world knowledge along with more formal scientific concepts in their knowledge framework in order to engage in sensemaking. The worksheet, with its real world and theoretical cueing, along with the scientific concepts and visualisations provided by the simulation, may have helped students in establishing this hybrid space where the students can bring their everyday experience into a more formal scientific framework, providing resources for sensemaking. This is consistent with findings from Sirnoorkar and Laverty (2021) that tasks based on real-world contexts promote students to use their lived experiences to generate explanation. The authors also state that the range of plausible values that students deduce from the problem statement can also influence students' attempts at sensemaking. This is also seen in the discussion about using resources from theories and prior experiences in the sensemaking of students.

The discussion also highlights how the inquiry-based classroom and the general classroom culture may have helped students to confidently use their ideas and prior experiences to engage in sensemaking. This was identified as an important element in classroom systems that encourage sensemaking by Deverel-Rico and Furtak (2025). The authors state that individual or group tasks that encourage students to incorporate their prior experiences into explanations or discussions can serve as resources for sensemaking better than whole-class discussion, which may trigger an answer-making frame in students (Deverel-Rico & Furtak, 2025). Sirnoorkar and Laverty, (2021) also suggest that the creation of hybrid spaces may have been triggered by the mechanistic representation of particles in the simulation and the worksheet, which has been found to cause students to more freely refer to everyday and formal knowledge.

Further, many groups include analogical thinking about particles to visualise and explain the behaviour of particles and the effect of particle properties on macroscopic properties of gas. This is related to findings from Louca and Zacharia (2023), where the authors claim that students relied on analogical reasoning when they could access known situations with similarities to the target phenomenon. This is seen explicitly in episode 5, where Betty uses the analogy of balls of different sizes to try to explain how size affects particle collisions. In the same episode, Ayden repurposes the analogy to explain how mass affects the speed of particles. Similarly, the effect of mass on the force of collisions is articulated in episode 1 and episode 3. This seems to suggest that students use analogical reasoning from thinking about particles similar to group 3 as balls colliding with each other and with the piston, with its mass and velocity affecting the force acting on the piston. This was the reason for several groups (group 1 episode 1, group 2 episode 3, group 3 episode 5) to predict, incorrectly, that increasing mass increased the pressure due to increasing force of collisions. Along with the incorrect use of analogies by Bruno and Teemu in the episodes mentioned above, it is seen that analogical reasoning can be also used to inaccurately relate to the target phenomenon, leading to misconceptions and wrong notions.

The idea that prior misconceptions affect the scientific validity of the student's reasoning was also seen in the episodes. In episode 2, Aino claims, incorrectly, that the volume of gas increases with an increase in the number of particles because the total volume of the particles is greater. Similarly, she incorrectly claims that the particle size and particle mass are correlated and larger particles are heavier than smaller ones. This misconception was also seen in groups 1 and 3. In Episode 1 by group 1, Andrea claims that particle size does not change without changing the mass of the particle. In Episode 5 by group 3, the students go back and forth between particle size and particle mass in their reasoning through the analogy of balls. Ayden initially rejects the idea introduced by Carl that size and mass are correlated, but later in the episode he advances an argument by stating that "*… big balls… they're sort of bigger and heavier.*" In Episode 6, Bruno confuses the setup conditions of the system they are looking at by saying that it may be connected to a pump as he thinks pressure increased with volume.

The episode above illustrates how the simulation itself can lead to certain misconceptions and incorrect reasoning by students. This may be seen in episode 6, where a glitch in the simulation made Bruno think that as volume increased pressure increased too. This unexpected outcome was used by Bruno to emphasise his reasoning later that the system is connected to some external device like a pump which increases the pressure. This makes him believe incorrectly that increase in internal pressure of the gas increases volume of the gas. Aino's misconceptions too may have been reinforced by the representation of the particles in the simulation. As the simulation showed particle volume to be of similar magnitude as the volume of the gas, Aino may have thought her thinking about particle volume is correct. The misconception related to size and mass of the particles may also have been reinforced since Aino believes that you can tell by looking at the simulation that the bigger particle size correlates to heavier particles. This may have been due to how the simulation represented size of the particles and how it affected the movement and collisions of the particles.

The episodes also highlight some confusion in many students' thinking. For example, in episode 2 by group 2, the students show confusion in their reasoning by confusing cause and effect with respect to volume and pressure. When reasoning about how pressure and volume are linked Cia initially starts off by discussing how pressure affects volume. During the course of her reasoning, she comes up with a mechanism for how decreasing volume increases pressure. In episode 6, Gina seems to claim that the ideal gas equation does not apply in their case since they feel that an external device is connected to the system. She does not seem to realise that any increase in pressure and volume then is caused by increasing particles of gas and the ideal gas law still holds. Bruno is then confused by what pressure means in the system they are analysing. This leads to Bruno's incorrect use of analogies to try to explain his thinking. As seen previously, most students had some confusion in their conception of how particle mass affected temperature, volume and pressure. In episode 9, Teemu jumps to the conclusion that there are no attractive forces in methane since it is lighter. This is not supported by any evidence in their discussion. Also, he claims that lesser attractive forces means that there will be wider pressure fluctuations as compared to oxygen. This conclusion is also not supported by any evidence. Thus, the link between claims and evidence is missing in Teemu's reasoning.

The lack of clarity in reasoning seen in the episodes is similar to the epistemic uncertainty from Ha, Chen, et al. (2024) which is described as students struggling to explain a phenomenon while analysing patterns, shaping rigorous evidence and using reasoning to overcome gaps in existing understanding. These results also show the limitations of using simulations as a pedagogical tool, in line with previous research by Akaygun and Jones (2013) where the authors state that students may develop incorrect understanding at the submicroscopic level as a result of visualising interactive animations. They posit that simulations may cause students to split their attention ineffectively while trying to attend to multiple representations or representations that change over time, leading to incorrect assumptions about the phenomenon (Akaygun & Jones, 2013). These findings lend weight to Bai's (2026) recommendation that student misunderstandings in the ideal gas law emphasize the need for explicitly teaching linkages between microscopic processes and the macroscopic behaviour of gases. In terms of pedagogical implications, instructors may need to be on hand to challenge such misconceptions in the students, since without proper feedback on errors, the students' misconceptions may impact later learning which builds on the mistaken mental model created by the student (Bennion et al., 2025).

In terms of the effect of simulations on sensemaking, the results demonstrate the students' use of affordances of simulations in their sensemaking in diverse ways as suggested by literature (Hunter et al., 2021; Haraldsrud & Odden, 2024). Most of the episodes involved the students using the explorative affordance offered by the simulations. Since the worksheet was designed in a way where the students used the simulation after they had made a hypothesis about the questions, the students often used the simulation to explore this hypothesis. This is especially the case in the question set dealing with the ideal gas laws and non-ideal parameters which may have an effect of the gases (episodes 1, 2, 3, 5 and 6). In episode 1 by group 1, Andrea explicitly states that they will assess their hypothesis about the effect of particle mass, particle size and particle attraction on macroscopic properties. The group then systematically explores all the variables in the simulation by varying one variable each in a series of steps that seems to generate evidence for their hypothesis, using which they strengthen their reasoning. This is similar to episode 5 by group 3, where the students also use the simulation's explorative affordance to check their hypotheses. In episode 3 by group 2, Aino uses the simulation to explore the effect of particle mass on pressure when Birgitta is unsure if increasing mass may cause the particles to hit the piston with more force. In this episode, the explorative affordance of the simulation seems to sustain sensemaking when students faced some confusion in their thinking. By using the simulation to "*try something with particle mass to see if the pressure keeps increasing*" Aino and her group mates explore the relationship between the variables in a way that promotes further discussion without stopping when they were unsure. The simulation, here, acts as a resource through which they can extend their knowledge resources to further engage in sensemaking.

The explorative affordance is used sometimes even when the students answer the other questions from the worksheet. In episode 8 by group 5, Teemu uses the simulation to explore the effect of temperature change on pressure. Since the volume can change in the simulation, the students cannot directly use the simulation to check this relationship. Teemu devises a comparison experimental set up to check the pressure and temperature deviation when the volume remains the same in two different scenarios. This is possible because the simulation offers the ability to explore the effect of multiple variables. In episode 9 by group 5, Emma tries to use the simulation to explore the way in which methane liquefies more easily than oxygen. She explores if the particle attraction is affected by particle mass to see if lighter methane particles can clump together more easily than heavier oxygen particles. Though, they do not discuss the relationship clearly, they find that lower particle attraction leads to lower volume, which they use as evidence to claim that methane is likelier to face larger pressure variations than oxygen. As seen previously, the reasoning is unclear and not correct, though the experimental idea of checking the effect of mass on attraction seems to have some merit for exploring the situation. Thus, we see that though the explorative affordance does not lead to conceptual understanding, it does seem to demonstrate more engagement in sensemaking practices. This finding is in line with findings from Haraldsrud and Odden (2024) and Hunter et al. (2021) where it was seen that even though simulations led students into sensemaking, they made incorrect conclusions through the use of incorrect scientific reasoning.

In many episodes, we see the feedback affordance of the simulation used by the students along with the explorative affordance. By providing immediate feedback, the simulation seems to help build confidence in the student's reasoning. In episode 1 by group 1, when the students get feedback from their exploration that the volume of the gas decreases as particle attraction increases, Andrea finds it "*…weird."* She uses the feedback as a starting point for refinement of their explanation. She offers a mechanism through which volume may decrease with increasing particle attraction. On the other hand, earlier in the episode when the group finds out that the particle mass is not related to volume, the students do not try to reason why the simulation output does not match their initial reasoning. This is similar to episode 5 by group 3, where the simulation output contradicts their view that an increase in particle mass will increase pressure or volume in the gas. The simulation output also contradicts their view that increasing particle size would decrease temperature due to the increase in volume. Even here, the students accept the simulation output as truth but do not question the reasoning that led them to this hypothesis.

In Episode 6 by group 4, a glitch in the simulation made the students think that the pressure and volume increase when the number of particles increase. This causes Bruno to reason that there is an external device connected to the tank which causes this output. Even after Gina explores the pressure and volume relationship again, showing that they are indeed inversely proportional, Bruno holds onto the initial feedback from the simulation as fact and tries to explain away the apparent inconsistency in the simulation as due the difference between "*the* *pressure of the system… the internal pressure"* and "*external pressure"*. In contrast, in episode 2 by group 2, Cia uses the feedback affordance to explain to Birgitta why she thinks pressure increases when volume decreases. She is trying to connect the increasing pressure to lesser surface area for collisions of particles to happen and states that since the force of collision has not reduced, the reduced area for collisions makes the pressure higher. When Birgitta asks her for clarity on what she means by decreasing area, she uses the feedback and representational affordances to quickly compare two scenarios, one with higher pressure than the other and points out the reduced area in the scenario with higher pressure to Birgitta. The feedback affordance seems to be related to Carpenter and Sullivan's (2017) notion that an interactive simulation that provides dynamic feedback to students will allow them to iteratively test their collective understanding of the topic. The authors see the simulation as not just a repository of content but rather as a participant in the group's discussions, providing confidence when students might have been stuck without hope of help. Thus, the authors assert, the interactive tool helps create conversations among students, which may open up ways to catalyse sensemaking (Carpenter & Sullivan, 2017).

The discussion of episode 2 above also illustrates the students' use of the representational affordance of the simulation. By pointing out the reduced area in which the collisions take place, Cia makes it easier for Birgitta to understand what she means. The representation of the situation in the simulation offers this opportunity for collaboration between Cia and Birgitta, where the representation stands as a way to link the thought process between them helping them in creating shared understanding which is the overlap of understanding among members in a group which changes as progress is made by working together through the process of updating individual understanding using feedback from each other (Mulder et al., 2002). In episode 1 by group 1, the representation of particles clumping together provides evidence for the students' thinking about the effect of particle attraction. Andrea in particular seems to be happy and claims that the particles clump together "… *[l]ike I said!"* which seems to indicate that the visual confirmation of her hypothesis builds confidence in her reasoning. This seems to support findings from previous research such as Penn and Ramnarain (2019) where student teachers reported a positive influence on affect including joy and autonomy. This is also relevant to the finding from the thematic analysis of written work that representational affordance is the affordance most perceived as useful in their sensemaking by students themselves.

The representational affordance also induces some mechanistic thinking when students engage in sensemaking. In episode 5 by group 3, the students use the representation of particle collisions in the simulation to make sense of why the volume increases when particle size increases. Betty claims that since the surface area of the particles has increased, the probability of collisions between particles increases, leading to higher number of collisions and thus to increased volume. Thus, the particle level representation has helped the students in their discussion, with useful facts that they use as evidence in their reasoning. This is also seen in many cases where mechanistic reasoning proceeds from the visualisation offered by the simulation. As shown before, many episodes have instances of mechanistic reasoning where the students think about the effect of particle collisions on volume and pressure. The students also think about the effect of particle speed and movement on temperature. Though it can be debated whether the mechanistic thinking was caused by the visualisation, the fact that the students often made hypotheses about the behaviour of particles and seemed to check that using the simulation, offers some evidence that the representational affordance of the simulation helps the students in their reasoning or at least in building confidence in their reasoning. The simulation may have played a role of a digital mediator, which has been found to play an important role in facilitating the creation of shared understandings through interactions between groups (Silvola et al., 2025). These findings also relate to Carpenter and Sullivan's (2017) contention that an interactive simulation that helps in visualising the microscopic world of particles and is shared between students may facilitate more communication among students, since they can use the representations as a stand-in for their lack of precision in the use of the scientific language of chemistry.

This use of representational affordance is shown in episode 8 by group 5 when Emma notices that because the piston is movable, the pressure remains constant even when there is more temperature, but the volume increases, which is not similar to the situation of the oxygen tank. Thus, the representation of the situation in the simulation helps Emma understand that she needs a different way of approaching the problem, which leads the group to try comparing the pressure and temperature in two separate scenarios by keeping the volume the same. This shows that sensemaking was sustained due to the fact that Emma attended to the moving piston in the simulation as a point of importance. This idea of attending to particular areas of the simulation through its representational affordance is seen in other episodes too. In episode 6 by group 2, the piston moving makes the students try to "*figure it some other way*" leading to the students trying to sustain sensemaking by exploring other areas of the simulation to see if the pressure could be kept constant somehow. In episode 9 by group 5, the students use the simulation output when checking if particle attraction is related to particle mass by noticing that increasing particle attraction decreased the volume. Teemu uses this as evidence to claim that the tank will undergo more pressure variation when filled with methane as compared to oxygen. By attending to the reduced volume through the representation of the situation, even though they were trying to see if particle attraction and mass are related, the students come up with ideas for their explanation building.

The above discussion also highlights the uncertainty affordance of simulations as they aid sensemaking in students. The uncertainty affordance of simulations can be highlighted by what students do when the simulation throws up output which is expected by the students versus when the output is unexpected. From the results it is seen that when the simulation output confirms the hypothesis the students have made earlier, the students quickly move on without building on their hypothesis. In many cases where the simulation output is unexpected, such as the particle mass not affecting the macroscopic properties in episodes 1, 3 and 5, the students still do not probe into why their initial reasoning is not correct. But in some cases, this uncertainty in output is used by students fruitfully to engage in sustained sensemaking. It is seen in episode 1 by group 1 where, as seen before, Andrea finds it weird that volume decreases with an increase in particle attraction, as the group hypothesised that volume would increase. This uncertainty created by the unexpected output from the simulation leads to a refinement of their explanation, which now is changed to reflect this new evidence from the simulation.

Similarly, the unexpected outcome in episode 6 by group 4 where Bruno tries to make sense of the glitch in the simulation, highlights that the uncertainty afforded by the simulation helped the group sustain their sensemaking by keeping them in the sensemaking frame while they created an explanation that fit with the perceived simulation output. In episode 8 by group 5, the students find that the volume is not the same when comparing the volume when the pressure is halved and the temperature is halved. This unexpected output leads to further explanation building, where the students try to figure out why the simulation output was different from their expectation. The students claim that the discrepancy in the simulation may be because the gas is non-ideal. They check the simulation again and see that the volume is close enough to equal when the pressure is halved and when the temperature is halved. This makes Teemu say that since the gas may be non-ideal the volume is close enough to be considered the same. This gives them confidence in their conclusion. These findings seem to confirm the findings from Ha, Chen, et al. (2024) and Ha, Park, et al. (2024) that student uncertainty is an important factor that enables and drives sensemaking. They consider the need for students to seek coherence between the new knowledge, which causes the uncertainty, and the prior knowledge which they use as resources, as the mechanism through which this uncertainty initiates the sensemaking trajectory (Ha, Park, et al., 2024).

The fact that unexpected outcomes from the simulation are generally not followed up might also relate to the fact that expected outcomes are also not followed up with. Together, this seems to show that the students were using the simulation output for fact-checking most of the time and not as a resource for engaging in sensemaking. It might also be showing that the students seem to think of the simulation as a stand in for authority. This is seen clearly in episode 5 by group 3, where the students check their hypotheses about the effect of non-ideal particle parameters on volume, pressure or temperature using the simulation. When they find that changes in particle mass does not change macroscopic properties they do not try to reason why, but just state that their hypothesis is wrong and move on. Even when their hypothesis about particle attraction is correct, they do not reiterate their reasoning or draw attention to the mechanism, but state that their hypothesis is correct and move on. This is also seen in the written work by group 3. Their answers to questions related to hypothesising without the use of simulation is rich in mechanistic reasoning codes indicating a high level of mechanistic reasoning within a framework of explanation building. But their answers to questions where the worksheet asked them to use the simulation generally lacked mechanistic reasoning and almost always involved them stating whether their hypothesis was proven correct or not, without reiterating reasoning or building their explanation using new evidence from the simulation output.

This use of simulation as an authority is also seen in the way students express frustration when the simulation does not explicitly model the problem situation. It is also highlighted in the thematic analysis of written work, where students seem to state that the simulation might have been more helpful if it matched with the problem more closely by having a mode where volume could have been kept constant. In episodes 4, 7 and 8 we see students display frustration and annoyance that the piston in the simulation moves freely, which is dissimilar to the constant volume tank in the worksheet, which they are trying to check the safety of. Since they do not find a way to keep the volume constant, to check the pressure variation when temperature varies, they express frustration. Group 3 students, in episode 4, even state that they want a program in the simulation which can show them the model explicitly related to the problem they are solving. In this episode, the students resolve that there is not enough information to solve the problem.

In episode 7, group 4 students also face a similar issue where they are frustrated by the lack of an option to make the volume constant in the simulation. In contrast to group 3, the students try to "*figure it out some other way"* and continue sensemaking. Eventually their efforts are frustrated, and they end the episode by stating that the information is not enough. In episode 8, group 5 students face the same "*... annoy[ance]..."* which frustrates their efforts to check the pressure variation. Similar to group 4, the students decide to try to figure out how pressure varies. They devise a comparative experimental setup, where once they check the volume of the system with pressure halved and then they check the volume of the system with the temperature halved. They reason that since the volume in both these systems was close enough to being equal, halving the temperature leads to halving the pressure. They use this as evidence to claim that the tank is safe, as they have claimed that doubling the pressure is ok, using the analogy of a bicycle tire.

The discussion above shows that the uncertainty affordance offered by the simulation can help in sustaining sensemaking in students, but it depends on their willingness to try to continue with explanation building. There may be many reasons for the differences in the approach of different students that was seen above. The way the worksheet was structured may have influenced students from group 3 that the simulation should be used only for checking their hypothesis, and thus, when faced with a situation where they cannot directly do that, they may have thought that the simulation was not enough. The students seem to have stepped outside the sensemaking frame when presented with what is termed as material resistance (McLaughlin & Farris, 2025). McLaughlin and Farris (2025) assert that the students viewed the simulations as a means to replicate the exact phenomenon, rather than as a tool for exploring the scientific concepts to understand them better. This created in the students a sense that this material resistance was a barrier to their understanding, rather than as productive means of engaging in explanation building through collaborative critique (McLaughlin & Farris, 2025). The authors also state that students may position themselves as consumers of the simulation, without agency to question the outputs or the ability to test different variables. In such cases, students may interpret the simulation as fact, without further critical inquiry (McLaughlin & Farris, 2025). In their study, the authors suggest that the users of the simulation may become disillusioned by the simulation if they notice that it is fallible and not all-encompassing. This was related to the users requiring literal similarity between the problem statement and the simulation used to explore the issue, which is similar to the groups' frustration at the simulation not meeting the exact specifications given in the task.

The episodes discussed above also indicates the role played by the worksheet in the sensemaking episodes. As seen in the chapter till now, the simulation has been used as a resource for sensemaking by using its multiple affordances in diverse ways by the students. But sometimes, the simulation was also used as a mechanism for factchecking the hypothesis generated by the students. This may have been because of the way the worksheet was structured. In the worksheet, the students had to predict what would happen, before they could explore the problem using the simulation. The wording used when asking the students to explore the simulation was "Did the simulation confirm your earlier hypothesis or did it make you reconsider?". This may have made the students use the simulation as more of a fact checking resource that gave the correct fact after the students had spent time reasoning. Also, the students may not have used the simulation as a means of collecting evidence for reasoning since the reasoning step had preceded the introduction of the simulation. This may have caused the students to think that there was no more reasoning required after viewing the simulation. Thus, the worksheet may have inhibited sensemaking with simulations. This could have been reduced by including more questions where the students used the simulation while generating their hypothesis. The rigid, predict, observe and explain cycle could have been loosened by making the students articulate revised reasons after their engagement with simulations too. Explicit questions around what they noticed from the simulation and how that shaped their reasoning could also have made students think about the simulation as a resource more often.

In contrast, a positive role the worksheet played was seen in the way the collection of setup conditions from the worksheet triggered the sensemaking episodes. In the analysis of entry conditions, the results showed that students articulating the question from the worksheet does indicate sufficiently that they enter the sensemaking frame as discussed by Hunter et al. (2021). It can be seen by the fact that they quickly assemble the knowledge resources they possess by articulating what they know (Odden & Russ, 2018). For example, in episode 3, Aino puts forward the fact that heat is related to kinetic energy of the particles. The group uses this as a resource in their sensemaking later in the episode while thinking about how the particle collisions are affected by mass. In episode 4, Carl starts off the discussion by stating that oxygen may be in liquid state at the temperature range in Mars. The sensemaking discussion later used this as a resource to try to build explanations about tank safety. This is similar to the discussions in episode 7 where Bruno brings up the notion of liquid oxygen in the beginning of the episode. Gina then uses the worksheet to state that maybe the particles stay in the gaseous state, since the worksheet mentions that oxygen gas is filled in the tank. In episode 6, Bruno starts the discussion by articulating the fact that volume is inversely proportional to pressure. This leads to further discussions about the mechanism through which this relationship is realised in the microscopic realm. In episode 9, the students enter the sensemaking frame by assembling together their knowledge on the structure and molecular masses of oxygen and methane molecules. This finding supports Palm's (2008) contention that task features that promote authenticity, can positively affect the students' engagement in the context.

The worksheet also presented itself as a resource for sensemaking when students turned to it to clarify certain facts or used the wording in the worksheet as evidence for their reasoning. This is seen in episode 4 group 3 where the students face uncertainty in their thinking due to the way the problem is framed in the worksheet. Betty states that she is confused when the worksheet states the tank is "*… full of oxygen…".* She is unclear at what temperature the tank is filled at since it might have a bearing on their reasoning. In the episode, this uncertainty sustains the sensemaking as the students discuss the effect of initial conditions under which the gas may have been filled in the tank and its effect on the safety of the tank. This is similar to the discussion in episode 7 by group 4. Here, Gina uses the description of the problem from the worksheet to claim that since the tank is full of oxygen, the tank may explode it the pressure increases. Gina uses her claim to reason that if the tank is filled at the lower end of the temperature range, the pressure increase will be too much for the tank to withstand, and so the tank should be filled when the temperature is at the higher end of the expected range. Gina had previously used the wording from the worksheet to argue that the oxygen gas will not liquefy at the temperatures of Mars. Thus, the worksheet allows the students to engage in thinking about real-world scenarios which help sustain sensemaking.

This interplay between the worksheet and the simulation is an important implication in terms of the usefulness of simulations in an inquiry-based lesson, when the instructor wants to invoke sensemaking discussions between students. The uncertainty generated by the simulation and the worksheet can often trigger sustained sensemaking if the students try to attend to that as the main aim of the exercise. If the students slip into answer-making or authority asking, the teachers can guide the students back into a sensemaking frame by helping them negotiate uncertainty and frustration and responding to learners' sensemaking, and instructional designers may offer ways of anticipating how uncertainty is likely to appear. Explicitly stating that creating sensemaking discussions is the goal of the session may help students remain in the sensemaking frame and sustain sensemaking even when there is frustration at the seeming discrepancy between the simulation and the worksheet. It can be argued that this discrepancy is, indeed, necessary for sensemaking, as otherwise a perfectly matched simulation and problem may lead to simple answer-making where the students use the simulation as a calculating tool or a fact checking tool. This is similar to how Conrath et al. (2025) saw teachers use uncertainty in a digital curriculum to engage students in sensemaking. In the study, students engaged in sensemaking if the teachers encouraged student discourse and argumentation. So, teachers can encourage students to discuss when they face uncertainty. Urging some caution, Hsiao et al. (2019) state that instructors need to explicitly attend to decoding of models in simulations to support students' thinking about the mechanisms governing the phenomenon under consideration, so that students do not confuse the simulated abstraction for reality.

Another implication for educators and curriculum designers here may be that more scaffolding and guidance might be useful for students when they are faced with potential cases of students using the simulation for fact checking or as authority. This might also illustrate the idea that in a shared collaborative task, students often converge cognitively on representations of authority (Puntambekar, 2006). Scaffolding from instructors in the form of prompts that encourage students to engage in further discussions activities might have helped to keep the students in a sensemaking frame (Puntambekar, 2006). This authority-seeking behaviour may be lessened by adding guidance on what is expected from the students, in the simulation or the worksheet. Interventions from the teacher or instructor may also be beneficial to the students to engage in sensemaking when faced with their hypothesis being found to be incorrect. This is in line with the findings from Kaldaras et al. (2024), where the authors state that learning activities accompanying the simulation can influence the range of student exploration. The authors argue that the simulation must be presented as an important characteristic within an authentic task, where students get to decide how to collect that data from the simulation. Recent research has found that instructional guidance in inquiry-based laboratory work should help students by pointing towards the relevant scientific theories to help activate cognitive learning while improving their level of learning even after committing errors (Kyynäräinen et al., 2026). The findings in this study also support Oh and Ha,'s (2025) formulation of sensemaking as a form of abduction. Using that framework, the authors recommend that science teachers identify critical evidence for students by making critical resources available to the students in the form of guidance or prompts. This may help students realize the meaning or usefulness of the knowledge that is being represented through the task and simulation.

The discussion on affordances of simulations also helps with analysing certain design features in the simulation which help students in sustaining sensemaking. The student discussion in the episodes clearly showed that hypothesis generation stage created many instances of explanation building and students engaging in sensemaking. This finding is similar to the findings from a study on epistemic practices within a virtual laboratory by Gavitte et al., (2025). In their study, the authors found that student talk during the virtual laboratory was focused on making predictions and understanding patterns, and that the virtual mode allowed students the opportunity to engage in experimentation by creating a need to analyse data and create new experimental plans (Gavitte et al., 2025). Thus, having simulations part of virtual laboratories with scope for students to generate hypothesis would seem to present opportunities for sensemaking. Similarly, the comparison feature in the simulation used in this study created more sensemaking opportunities for students where they could visualise two scenarios side by side, aiding the students to conduct several similar experiments and be able to compare their results with other results which may create many productive learning opportunities (Kluge, 2014).

Another important way in which simulations aid sensemaking in students is due to the elimination of cognitive load from translating back and forth from oral or written descriptions of the system, due to the presence of the dynamic representational models (Kaldaras et al., 2024). According to Kaldaras et al. (2024), a well-designed simulation drives students to explore features of a problem or task to match their level of understanding. This can be seen in the episodes where students use their prior experiences and knowledge of scientific theories to attend to certain key features that they identify as being important to solve the problem. Finally, as seen in a systematic review of simulations in chemistry education by Ortega et al. (2024), sensemaking can emerge if the simulation aids in the analysis of the problem on different levels (microscopic, macroscopic and symbolic). It seems that the tasks enabled students to bridge representation levels, encouraging the students in making meaningful connections through group discussions, while engaged in co-construction of knowledge (Moju et al., 2025). Emphasizing discussion among the students may also be seen as key to improving the development of inquiry competences which is seen in this study in the form of robust explanation building using the worksheet as a resource. The authors also point out that the instructional material that accompanies the simulation, must consider prior knowledge of the students while including guiding questions which is seen in the real-world problems that students solved in the worksheet (Ortega et al., 2024).

Within science education research, there has been a move towards a more practice and process-oriented teaching of science in the last few decades, taking in theoretical and pedagogical considerations from various disciplines and fields, with technology becoming one driver for innovation and change. The opportunities that various digital technologies offer for promoting learning with understanding for students at various levels of prior knowledge has made it an exciting field of pedagogical innovation. But to be effective takes more than just introduction of new technologies. This study has tried to understand mechanisms through which students engage in productive sensemaking with the use of interactive simulations as I feel that understanding these mechanisms may offer science educators, simulation developers and curriculum developers more insight into how and what processes affect such sensemaking. I have focused on sensemaking since I believe it to be an important part of the process of learning within an inquiry-oriented science education. If the students engage in sensemaking in science classrooms, I believe that they are more likely to learn scientific concepts, and more importantly, acquire science process skills which are most relevant in our times of misinformation and overinformation.

Through this study, I have explored the diverse ways in which students use computer simulations to make sense of chemistry concepts. It is seen that simulations promoted sensemaking when guided by scaffolded real-world tasks. One main finding was that students typically engaged in robust explanation building with the fluent use of mechanistic reasoning within their explanation building while engaging in collaborative critique to build their explanations together. This was seen across groups and across many different questions from the worksheets leading to confidence in the strengths of using computer simulations as a tool for sensemaking. One of the important moves used by the students in their sensemaking was the use of multiple scientific theories including the ideal gas law, from prior knowledge as resources to aid their sensemaking. Students also used analogies and analogical thinking while using everyday knowledge from their life contexts to sustain sensemaking in the face of ambiguous information. The wide prevalence of these moves provides compelling evidence for the presence of sensemaking epistemic form in the student discussions, which builds confidence in the application of these results to other relevant contexts too.

Simulations were seen to offer many affordances exploited by students to productively engage in sensemaking and some mechanisms through which these affordances operated in students sensemaking were also discussed. The results demonstrated the students' use of the explorative affordance of simulations to explore their hypothesis for the questions in the worksheet. The simulation acted as a resource through which the students extended available knowledge resources for engaging in sensemaking. In many episodes the feedback affordance of the simulation was used by the students along with the explorative affordance. By providing immediate feedback at the same time when exploring certain relationships, the simulation seems to help build confidence in the students' reasoning. The representational affordance of the simulation offered students the opportunity for collaboration, helping them in creating shared understanding, while inducing mechanistic thinking. The representational affordance also helped students to attend to important areas which helped them focus their explanation building. The uncertainty affordance caused by the unexpected output from the simulation helped students refine their explanation. The uncertainty affordance also sustained sensemaking in students when they tried to use the uncertainty productively to further discussion. The results also point out the important role the worksheet played in the sensemaking trajectory of students. While analysing entry conditions, it was seen that the worksheet triggered students to start assembling their knowledge resources by cueing them to certain important facts and conditions. The worksheet also presented itself as a resource for sensemaking when students turned to it to clarify certain facts or used the wording in the worksheet as evidence for their reasoning.

The results also showed some limitations of this approach to sensemaking, while steps to overcome these limitations were also discussed. In many episodes it was seen that the students accept the simulation output as truth. This seems to show that the students were using the simulation output for fact-checking most of the time and not as a resource for engaging in sensemaking. It might also show that the students thought of the simulation as a stand in for authority. It was discussed that better guidance through scaffolding with explicit instruction from teachers on the nature of simulation use for sensemaking may improve student efforts. The design of the worksheet could also be improved, with more questions included where students could use the simulation while generating hypotheses. The students also encountered frustrations, due to perceived limitations of the simulations. These could be avoided if teachers could support the students by asking guiding questions about how best to use the simulation in creative ways to overcome the limitations. Incorrect reasoning, misconceptions and incorrect facts used for sensemaking were also encountered in many episodes, showing the distinction between sensemaking and conceptual learning.

The pedagogical implications of the results were also discussed, with particular attention focussed on how guidance from the instructor and scaffolding prompts may help in productive sensemaking in their own classrooms. It was discussed that teacher demonstrations and a debriefing of selected issues after the lesson can aid in preventing misconceptions and incorrect reasoning to become issues later on. It was also discussed that specifically for instruction in gas laws, there is a need for explicitly teaching linkages between microscopic processes and the macroscopic behaviour of gases. Certain task features and characteristics of simulations that promoted sensemaking were also discussed, which may help designers and curriculum developers in their goal of creating resources for students to engage in sensemaking in science classrooms. In conclusion, the study demonstrated the strengths of the inquiry-based approach aided by the use of computer simulations in engaging students in scientific sensemaking, while also noting a few limitations which could be overcome with the use of explicit guidance and better scaffolding from the worksheet and teachers which may be crucial for students to be best able to use the affordances of such simulations in their sensemaking.

6 Limitations and scope for further research

The interpretation of results from this study should be contextualised with certain limitations related to research design, context and sample.

Firstly, the results from this study may not be generalizable to a large population since the sample was purposive and may not be representative. The students in the class were familiar with the inquiry based approach used in the session, which may not be the case in the population in general. This study presents a case for analysing sensemaking using a particular simulation using a specific activity designed purposefully for the goals of this research. This may reduce generalizability of the findings since the research was conducted by an external researcher with the specific intention of observing sensemaking and observer effects may have played a role in the data generated. The context of this study may also limit the generalizability of this study since the research was carried out in a specifically inquiry-oriented lab course for teacher students. While inquiry oriented teaching is becoming more widespread, it is not the default mode of science teaching and the effect of the familiarity of inquiry-based approaches with student led discussions may have been seen in the results of this study. Though ample evidence has been presented to support the results and the interpretations, it may be possible that with a class not familiar with inquiry-based laboratory work, more guidance or preparatory work may be needed to conduct a similar study. Future research can build on the design of this study to analyse sensemaking episodes in different settings, for example in a different topic using different simulations.

Secondly, the qualitative data analysis was conducted by only one person which may reduce the reproducibility of the study. Since the coding and interpretation was handled by one person, an element of bias in the analysis may have been present. Future research with similar research design might benefit from being conducted in teams of researchers. Also, since deductive coding was used in the analysis, there may have been scope for bias in the way that the researcher may have found what they were looking for. There may have been a possibility of overfitting certain discussions within the coding scheme than looking at the data without the bias from the theoretical lens. Though transparency and clear detailing of the data collection, data analysis and coding procedures may help in reducing bias, having another researcher may have helped decrease the bias further.

Another limitation of this study is due to the fact that the data analysis was done with a translation. Though care was taken to eliminate dubious reading from the translation tool, the fact that native speakers of Finnish were not involved in the translation of the transcript may have made it possible for errors to have crept in the translated version. Since the results depended on analysis of discourse which included scientific terminology, the lack of a professional translation is a limitation that may affect the authenticity of the results. Further research using similar designs need to ensure the presence of a professional translator or needs to be done using the language that the researchers are comfortable analysing on their own.

Related to the above, another limitation of the study is the fact that only verbal discourse was used in the analysis. Sensemaking research with students engaged with mechanistic reasoning has been fruitfully analysed using multimodal discourse analysis inclusing gestures, facial expressions, student diagrams and student created animations among other rich sources of data. This study chose to focus on verbal discourse analysis alone, since student talk is a major part of sensemaking and the research focussed on the argumentation tradition of sensemaking research with a focus on explanation building using constructive collaboration between participants. A study design with more multimodal analysis including gestures may have had different interpretations and may have halped in analysing certain aspects such as the frustration experienced by students or the entering and sustenance of sensemaking frames in more detail, which could have helped in a more in-depth study of the trajectory of sensemaking than was possible with the current design. Future research may try to incorporate multimodal methods of analysis as part of their research design to get a more detailed picture of the sensemaking trajectory of students.

Finally, though sensemaking is related to conceptual understanding, and indeed learning with understanding is an aim for seeking to uncover the mechanism of sensemaking among students, eveidence for sensemaking is not evidence for scientific understanding of the concepts. As seen in the results, sensemaking discussions may often include non-normatice reasoning and the students may arrive at incorrect conclusions or use incorrect facts or claims as evidence, which may not lead to conceptual understanding. Further research is needed to look at conceptual understanding or conceptual change frameworks along with the sensemaking processee to indicate how sensemaking relates to understanding of scientifically correct concepts and how sensemaking may mediate learning in an inquiry-based classroom.

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Appendices

Appendix 1 Student Consent Form

This form asks for your consent to collect data during this simulation-based learning activity as part of my master's thesis research at the University of Turku.

What is the activity?

You will take part in a structured chemistry learning activity focused on gas laws and scientific sensemaking. During the activity, you will work in groups to solve problems using an interactive simulation, discussing ideas with peers, and explaining your reasoning in spoken and written form. The whole activity will be recorded on audio and/or video

Why is this activity being conducted?

The activity will be used to better understand how students make sense of scientific ideas using simulations. The findings may be used to improve teaching practices and for educational research.

Is participation voluntary?

Yes. Participation in this activity is voluntary. You may choose not to participate or to withdraw at any time without penalty. Non-participation will not affect your grade, assessment, or standing in the course.

How will data from the activity be used?

- Recordings will be stored securely on University of Turku systems before being transcribed and then deleted
- Transcripts and written work will be anonymized. Only the anonymized transcripts and written work will be used for analysis.
- Only the researcher and academic supervisors will have access to the data

Your rights

You can withdraw your consent at any time before the data is anonymised. You also have the right to access your data and request correction. After anonymisation, individual data can be difficult to be identified.

Consent

I have read and understood the information above. I voluntarily agree to participate in the simulation-based learning activity. I also agree to be video/audio recorded during the activity and agree that my written work during the activity can be used as data for research purposes.

Name: ________________________________

Signature: _____________________________

Date: __________________________________

Appendix 2 Privacy Notice

1. Title of the register
Using computer simulations as a tool for sensemaking in a university chemistry course

2. Data Controller
Responsible person: Nandagopal Thangavelu,
Email: nantha@utu.fi,

3. Purpose of processing personal data
The activity is part of master's Thesis work for the Masters in Educational Science at the University of Turku. The activity investigates how students use simulations to support sensemaking in chemistry. Students' discussions, explanations, and interactions with simulations will be audio and/or video recorded.

4. Legal basis for processing (GDPR Article 6)
Processing is based on the data subject's informed consent (Article 6(1)(a) GDPR). Participation in recording is voluntary and not required for course completion or assessment.

5. Categories of personal data
• Video and Audio recordings
• Written responses produced during the activity

6. Recipients of personal data
The data will only be accessed by the researcher and, if applicable, academic supervisors at the University of Turku. Data will not be disclosed to third parties.

7. Transfer outside the EU/EEA
Personal data will not be transferred outside the EU or EEA.

8. Principles of data protection
All personal data collected from the respondents will be processed in accordance with the General Data Protection Regulation (GDPR). The data will be stored on the servers of the University of Turku. Personally-identifiable data will be removed during the analysis phase.

9. Data retention
The recordings will be transcribed using tools approved by the university. The transcripts will be pseudonymized so that the data can be archived in an anonymized form on the servers of the University of Turku. The data will be permanently deleted immediately after the thesis has been completed but by 1 December 2026 at the latest.

10. Rights of the data subject
The data subject has the right to access their personal data retained by the Data Controller, the right to rectification or erasure of data, and the right to restrict or object the processing of

data. The right to erasure is not applied in scientific or historic research purposes in so far as the right to erasure is likely to render impossible or seriously impair the achievement of the objectives of that processing.
The realisation of the right to erasure is assessed on a case-by-case basis.
The data subject has the right to lodge a complaint with the supervisory authority.

11. Voluntary participation
Students may participate in the activity without consenting to recording. Non-participation will not affect your grade or standing.

12. Information on the source of personal data
The data is collected directly from those who participate in the study.

13. Information on the existence of automatic decision making, including profiling
The data will not be used for automatic decision-making or profiling.

Appendix 3 Simulation Activity Worksheet

Q1. Introduction

In this activity, you will explore how different variables affect the behaviour of gases by forming initial hypotheses, using an interactive simulation to test them, and applying your observations to real-world scenarios.

Through guided questions, particulate-level sketches, and reasoning tasks you will connect your findings to the ideal gas law.

NB: As you work through each question, make sure to explain your reasoning in full detail. Your written explanations are an essential part of this activity and the research, so please take your time to describe your thinking clearly and thoroughly as if you are going to be evaluated on these answers, or would be explaining this to someone else.

For the hypotheses below, imagine a system with a piston with gas inside it, where the piston can freely move, that is, the volume of the gas can change.

Hypothesise: What will be the relationship between
a) Volume and number of particles of the gas

b) Volume and Temperature

c) Volume and Pressure

Now use the simulation to test your hypotheses:

1. Use the simulation to explore the relationship between volume and number of molecules. How does the volume change when you change the number of molecules? Did the simulation confirm your earlier hypothesis or did it make you reconsider?

2. Use the simulation to explore the relationship between volume and temperature. How does the volume change when you change the temperature? Did the simulation confirm your earlier hypothesis or did it make you reconsider?

3. Use the simulation to explore the relationship between volume and pressure. How does the volume change when you change the pressure? Did the simulation confirm your earlier hypothesis or did it make you reconsider?

Q2. Mars Tank Sensemaking Activity – Part 1
Solve the following problem. Explain your reasoning wherever possible.
You need to test an O_2 storage tank for potential use as part of a NASA mission to Mars.

Knowing that Mars follows a highly elliptical orbit, and thus temperatures vary significantly as the planet travels around the Sun, you take it upon yourself to validate the manufacturer's statement that the tank is "designed to meet a wide range of low temperature requirements". The O_2 tank is marked safe against sudden rupture at capacity from - 100 °C to - 0 °C.

a) Sketch a particulate-level representation to describe the gas molecules inside the tank (1) in the -100 °C and (2) -0 °C . Assume the volume is held constant.

b) Hypothesise: Will the tank be safe at the temperature extremes seen in Mars if it is carrying its full capacity of O_2? Explain your reasoning.

Now use the simulation to test your hypothesis:
(NB: For the parameters you do NOT use, retain the default values)

1. Will the tank be safe at the temperature extremes seen in Mars? Explain your reasoning.

2. How did your exploration of the simulation support confidence about your reasoning? Could you describe how that was the case?

Q3. Exploration – Part 2:

Hypothesise: What will be the relationship between
a) Volume, pressure and temperature with particle mass. Explain your reasoning.

b) Volume, Pressure and Temperature with particle size. Explain your reasoning.

c) Volume, Pressure and Temperature with particle attraction. Explain your reasoning.

Now use the simulation to test your hypotheses:

1. Use the simulation to explore the relationship of volume, pressure and temperature with particle mass. What changes, if any, do you observe as particle mass increases? How did it relate to your hypothesis from the previous section?

2. Use the simulation to explore the relationship of volume, pressure and temperature with particle size. What changes, if any, do you observe as particle size increases? How did it relate to your hypothesis from the previous section?

3. Use the simulation to explore the relationship of volume, pressure and temperature with particle attraction. What changes, if any, do you observe as particle attraction increases? How did it relate to your hypothesis from the previous section?

Q4. Hypothesise:
1. Imagine now that you are designing a tank for storing huge amounts of CH4 to be used as fuel in Mars. Do you think this could be the same tank as the O2 tank, or would this require a different tank? What data about CH4 as compared to O2 do you need to answer this question? Can you explain your reasoning?

2. What features of the simulation could you describe that helps with your reasoning?

Appendix 4 Pre-session Questionnaire

1. Using simulations will help me develop a deeper understanding of chemistry concepts.
2. I expect simulations to be easy for me to use during learning activities.
3. Simulations will help me get the most out of my time in learning chemistry.
4. The learning carried out through simulations will be clear and easy to understand.
5. Simulations can improve my performance in chemistry laboratory work.
6. Simulations are a flexible technology to interact with.
7. It will be interesting to use simulations for learning chemistry concepts.
8. I have the intention to use simulations to learn new concepts in chemistry.
9. The use of simulations will promote good experimentation habits.
10. The use of simulations will be beneficial for my learning in chemistry.

Appendix 5 Post-session Learning Questionnaire

1. Using the simulation helped me develop a deeper understanding of concepts related to gas laws.
2. I found the simulation to be easy for me to use.
3. The simulation helped me get the most out of my time while learning.
4. The learning carried out through simulations was clear and easy to understand.
5. Simulations improved my performance in chemistry laboratory work.
6. The simulation was flexible to interact with.
7. It was interesting to use simulations for learning about gas laws.
8. I have the intention to use other simulations to learn new concepts in chemistry.
9. The use of simulations promoted good experimentation habits.
10. The use of simulations was beneficial for my learning.

Appendix 6 Post-session Teaching Questionnaire

1. Using simulations will help my students develop a deeper understanding of chemistry concepts.
2. I expect simulations to be easy for my students to use during learning activities.
3. Simulations will help me get the most out of my student's time in learning chemistry.
4. The learning carried out through simulations will be clear and easy to understand for my students.
5. Simulations can improve my students' performance in chemistry laboratory work.
6. Simulations are a flexible technology to interact with for students.
7. It will be interesting for my students to use simulations for teaching chemistry concepts.
8. I have the intention to use simulations to teach new concepts in chemistry.
9. The use of simulations will promote good experimentation habits in students.
10. The use of simulations will be beneficial for my students' learning in chemistry.

Appendix 7 Post-session Sensemaking questionnaire

1. While working with the simulation, I felt we had to make decisions about how to explain the phenomenon, not just choose the correct answer.
2. While working with the simulation, I felt we were trying to figure out how the system works, rather than trying to get the right answer.
3. While working with the simulation, I felt we were actively changing variables and observing outcomes to resolve gaps in our understanding.
4. While working with the simulation, we actively revised our initial ideas when the results did not match our expectations.
5. While working with the simulation, we were actively constructing explanations of the phenomenon using scientific concepts and representations.
6. While working with the simulation, we evaluated which observations supported or contradicted our explanations.
7. The simulation encouraged us to stay focused on figuring out the phenomenon, rather than quickly looking for answers.