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SI: FAMILY RESEMBLANCE APPROACH

Let them *research with*

Using history of science to teach upper-secondary chemistry students about the nature of science

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Abstract
The French natural philosopher Henri Victor Regnault (1810–1878) was one of many researchers who contributed to the development of the thermometer in the 19th century. In this paper, we use an example from Regnault's work to explore how the history of thermometry can provide a context for teaching upper-secondary chemistry students about the nature of science (NOS), particularly its aims and values. The study takes form as a hermeneutical spiral, wherein literature on the history and philosophy of science, NOS, the family resemblance approach (FRA), NOS teaching, characteristics of narratives, and the new performative paradigm feed into the spiral, along with input from an empirical study. A teaching unit (n = 21, duration = 90 min) was developed and tested on Norwegian students aged 17–18 years, and a thematic analysis of students' statements (n = 13) was carried out. The students identified "being first," "usefulness," "accuracy," and "minimalism" as values and aims that guided Regnault's work. We argue that the use of this particular historical episode framed within FRA (1) invited students to identify with the human actor—Regnault, (2) invited students into the historical context of the development of the thermometer, and (3) demonstrated complexity and provided context to support students' own construction of their understanding of NOS. To summarize, by deriving the term "research *with*" from the performative paradigm and using the context of the historical episode related to the thermometer within the FRA framework students were invited to research *with* Henri Regnault.

Keywords FRA · NOS · Aims and values in science · History of thermometry · Research *with* · Re-enactment · Pedagogical history

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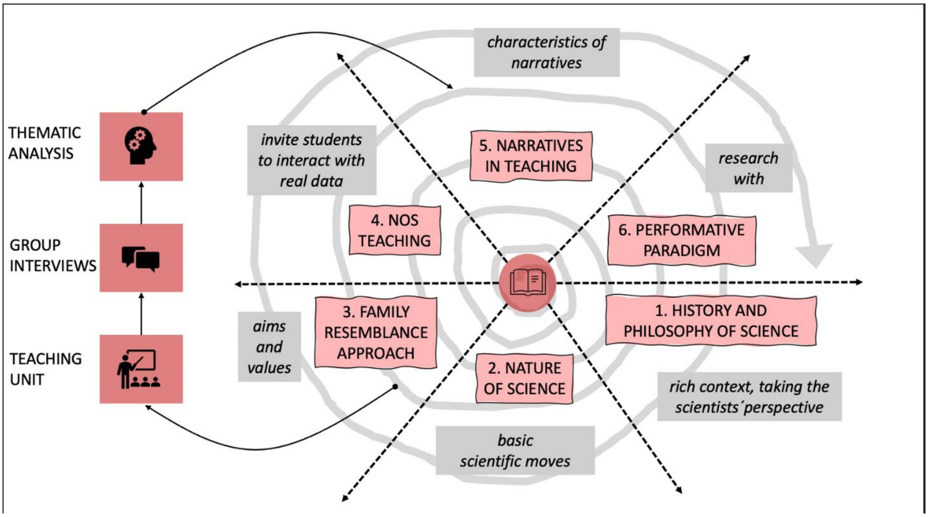

Fig. 1 Study overview illustrated with a hermeneutic spiral. The spiral starts with immersion in a historical episode, as described in Chang (2004), followed by an expansion of its horizon through research literature, and then a detour in the form of a teaching unit, group interviews, and a thematic analysis. Drawn by Camilla Berge Vik

1 Introduction

As early as the 17th century, thermometers and their predecessors, thermoscopes, were available for the measurement of temperature differences (Turner, 2013). However, as these devices were not standardized, they often provided inconsistent readings even in the same situations (Chang, 2004). Natural philosophers, at the time, were not satisfied with the performance of these instruments, as they reasoned that it was possible to have only one "true temperature" for a given situation. This, along with other issues, led natural philosophers in Europe on a search for the "true temperature" and a standardized way to measure it. This historical episode formed the starting point of our study, in which we sought to answer the question "Can an episode from the history of the thermometer serve as a context for teaching students about the nature of science, and if so, how?"

This study takes the form of a hermeneutic circle or spiral (Eger, 1992, 1993), as shown in Fig. 1. After our immersion into the historical episode, we gradually moved outwards through the input of literature in different fields, including the history and philosophy of science, the nature of science (NOS), the family resemblance approach (FRA) to NOS, NOS teaching, narratives in teaching, and the performative paradigm. This was accompanied by a teaching unit that was developed and tried out, group interviews, and a thematic analysis of the participants' responses, so as to represent the voice of the students in the study. In the teaching unit, students were invited to adopt the scientist's perspective and to interact with real historical data. The aim was to provide them with a view of the "basic moves" (Emden, 2021, p. 1055) of actual scientists and understand their aims and values through rich contexts and the characteristics of narratives. Finally, we used insights from the newly introduced performative paradigm proposed for post-qualitative and artistic research

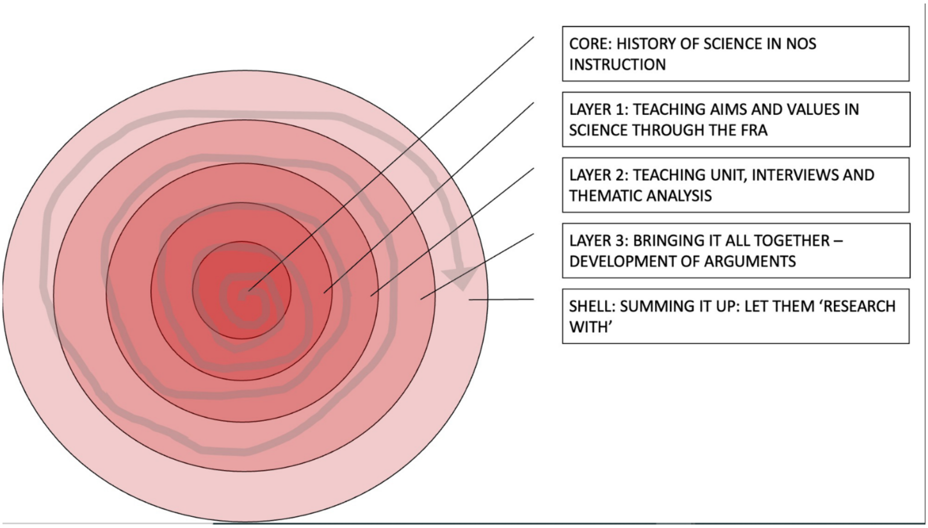

Fig. 2 Outline of the study process. The core of the study is the historical episode. The three layers represent teaching aims and values in science (layer 1), the teaching unit itself with interviews and thematic analysis (layer 2) and the development of arguments (layer 3). The shell sums up the study, in the term «research *with*». Drawn by Camilla Berge Vik

(Østern et al., 2021) to answer our research question ("Can an episode from the history of the thermometer serve as a context for teaching students about NOS, and if so, how?"). With its emphasis on closeness and complexity, the paradigm opens up researchers' participation in the phenomenon that is researched. Accordingly, in our study, we invited students to participate in the historical phenomenon of the development of the thermometer in the classroom. A performative paradigm produces space for movement in the subject being researched—from meaning to meaning-making, from subject to relations—where knowledge is created rather than discovered. We employ the term "research *with*" from the performative paradigm and argue that the historical episode invites students to do exactly this: that is, instead of conducting research *on* historical actors, they research *with* them, and in this way, co-create their own understanding of NOS and, particularly in the context of this study, aims and values. The current study is, therefore, not a traditional qualitative empirical study, but one which capitalizes on a rich historical case and research literature in different fields through a hermeneutical approach, as explained above. The empirical material is used to exemplify, explore, and suggest future directions for NOS teaching, rather than to present firm conclusions.

In Fig. 2, we lay out the different stages of our study and its justification through five sections: a core, three layers, and a shell. The core is the historical episode and the justification for applying it in science teaching. The three layers are (1) aims and values in science and through the FRA framework; (2) the teaching unit, interviews, and the thematic analysis; and (3) the development of our arguments grounded in interpretations based on layer 1 and 2. Finally, we frame and summarize our findings through a shell. Instead of a separate literature review at the beginning of the article, the literature is intertwined throughout the five parts of the text in the following manner: for each turn of the hermeneutic spiral, which corresponds to one layer, we provide the literature that increased our horizon of understanding and our corresponding actions or reflections.

2 Core: History of Science in NOS Instruction through Henri Victor Regnault and his Investigations into Thermometer Fluids

We based our study on the premise that elements from the history of science, together with explicit reflections on NOS, can be effective in promoting adequate conceptions of NOS (Abd-El-Khalick & Lederman, 2000, p. 694). We were inspired by reports on NOS instruction that included the use of science stories (Clough, 2011; McComas, 2020a), rich historical examples (Allchin, 2004), historically based narratives (Hansson et al., 2019; Klassen & Klassen, 2014), and engagement with historical experiments and artifacts (Cavicchi, 2008; Chang, 2011; Eggen et al., 2012). Further, we were informed by reports on the benefits of giving students opportunities to interrupt (Dai et al., 2021) or interact with (de Berg, 2004) the historical episode and limiting the number of NOS aspects taught at a time (Dai et al., 2021). We decided to pay particular attention to aims and values, as this is an understudied aspect of NOS. Allchin (1999) suggested that values be taught reflexively, that values may well be taught through historical examples, like NOS itself, and that individual scientists and their thought patterns are particularly well suited to studying values in science.

Several frameworks for NOS have been described in the literature (e.g., Allchin, 2017; Matthews, 2012), the most widely used among them being the "consensus view" (Ledermann, 2007; McComas, 2020b) and FRA (Erduran & Dagher, 2014; Erduran et al., 2019; Irzik & Nola, 2011, 2014, 2022). FRA was selected as a promising framework for our study because it aims at providing a holistic overview of NOS, including both domain-general and domain-specific aspects of science, in which the social-institutional and cognitive-epistemic aspects of scientific practices are balanced (Erduran & Dagher, 2014; Erduran et al., 2019). Another important reason for selecting FRA is that it treats "aims and values" in science as an explicit category (within the cognitive-epistemic domain). However, it should be noted that both the consensus view and FRA have been criticized for undermining freedom of thought, in that knowledge in NOS is reduced to descriptions and that NOS becomes a static set of tenets or categories instead of a dynamic concept (do Nascimento Rocha & Gurgel, 2017). To overcome this limitation, in the teaching unit that was developed for this study, we do not place emphasis on static descriptions of categories and encourage open dialogue about aims and values in science.

We emphasize the need to base our historical episode on sound historiography and the best available sources that can inform us (Klassen, 2009; Klassen & Klassen, 2014). In this context, Chang's (2004) comprehensive book *Inventing Temperature*, which is about the history of temperature and the development of the thermometer from the 17th to the 19th century, appeared to be a good choice with its thorough, detailed account that drew on scholarship and expertise in history, philosophy, and science. This book also includes a comprehensive analysis of each chapter or theme in the book and is, therefore, particularly useful as an informed source for a teaching unit. Some episodes from the book were eliminated because they were considered to be too scientifically complex and, thus, too time-consuming to fit within the allocated time for this study. The investigation on thermometer fluids was selected as context for the teaching unit, as it was considered a suitable topic for chemistry students who were familiar with thermometers, both in their everyday lives and in the chemistry lab. Another reason was that the concepts of heat and fluids, which are central to the history of the thermometer, are also familiar to the students. Moreover, the history of the thermometer is an excellent example of how natural philosophers from different countries and across centuries participated in the same endeavor. We were drawn toward Henri Victor Regnault (1810–1878) as the main actor of the story, as the FRA category "aims and values" pointed to a character with clear agency, that is, a character that "must make choices and live by the consequences of those choices" (Klassen, 2009, p. 411). One of the pedagogical reasons for highlighting Regnault's contributions in the classroom narrative included easy accessibility to measurement data that could be adapted to a classroom context and which themselves could represent aims and values in science. Another reason was that Regnault subscribed consistently to what we describe below as the "comparability principle," and this made it possible to focus on one methodological principle. However, we were careful not to present Regnault as the "hero" of the story, but instead, made sure that his work was embedded in a larger scientific context. The goal was not to demonstrate Regnault's supremacy over other natural philosophers, but rather, to focus on a specific episode in order to build an understanding of NOS.

2.1 The Historical Episode

Regnault was not among the most famous French scientists of his time; however, Chang (2004) informs us in his seminal book that, at the peak of his career, Regnault was among the most triumphant scholars. He was an elected member of the French Academy of Sciences in Paris and enjoyed professorships at two of the most prestigious higher learning institutions in France. Regnault had become interested in heat and temperature because he was commissioned by the government to gather relevant experimental data and review techniques to investigate the steam engine. Having been fortunate to have the opportunity to build an impressive laboratory where he could perform measurements with the best available equipment at the time, he was careful to undertake the measurements in the most accurate manner. There were three major problems related to practical thermometry at the time: establishing which phenomena should be used as "fixed points" on the thermometric scale; finding the right thermometric substance or fluid, that is, one which expands uniformly with real temperature; and extending the thermometric scale beyond its original domain (Chang, 2004, 2013).

Regnault was one of the natural philosophers who were dissatisfied with the rigorous, yet unfruitful, theoretical attempts made in the tradition of so-called "Laplacian physics," which was prominent in the first two decades of the 19th century (Chang, 2004, 2013; Fox, 1974, 2013).[1] He and his contemporaries were particularly frustrated that thermometers showed different temperatures when applied in the same situation. To reduce the risk of his data being rejected by other natural philosophers, Regnault reduced the number of theoretical assumptions to a minimum. To this end, he found a solid basis in the concept of *compa-*

[1] Laplacian physics sought to reduce all phenomena of nature to actions that occur at a distance from particles of ponderable, as well as imponderable, matter and is named after the French natural philosopher and mathematician Simon Laplace (Fox, 1974). Regnault's precision measurements can be viewed in the context of the empiricist trend dominating post-Laplacian physics, which is far removed from the failed theorizing that marked the Laplacian tradition.

rability (Chang, 2004, p. 77). By applying this concept to the context of the thermometer, if a thermometer is to show the true temperature, (1) it must in a given situation always show the same temperature, and (2) if a *type of* thermometer is to show the true temperature, all thermometers of this type must show the same temperature. To accomplish this, he needed to find the best thermometric fluid and, thus, address the second of the three major problems described above. By using the concept of comparability as a basis, Regnault carried out many measurements using both the mercury and the air thermometer. He found that the type of glass the mercury thermometers were made of strongly influenced the measurement. At the time, there was no knowledge about how this influence could be reduced, as a sufficiently standardized way to produce the glassware was not available. Regnault, therefore, rejected mercury as a suitable thermometer fluid and focused his work on the air thermometer. To his fortune, the measurements with the air thermometer proved less dependent on the type of glass, and Regnault was able to proceed to testing other variables, such as air density and different types of air or gas. With the air thermometer, variations in air parameters resulted in only very small deviations in his entire measurement range, and this led Regnault to conclude that the air thermometer was the most promising (as it met the comparability criterion to the largest extent). He also used this criterion to argue further against alcohol as a suitable thermometer fluid (Chang, 2004, pp. 74–84). Yet, he pointed out that this did not necessarily mean that his preferred thermometer showed the "true temperature"—and indeed, he did not "solve" the problem. However, at the very least, Regnault managed to show that, with comparability as the criterion, the other fluids performed worse than air.

After immersion in a rich historical example within a suitable topic and a main actor, we now move outwards from the core of the hermeneutic spiral to elaborate on the chosen aspect of NOS: aims and values in science.

3 Layer 1: Teaching aims and Values in Science Through the Family Resemblance Approach

"Aims" and "values" are interrelated, and sometimes, the terms are used interchangeably. For example, aims for the scientific work can be considered as values for scientists who want their theories and models to realize their aims (Irzik & Nola, 2011, 2014). Accordingly, assessing credibility or usefulness (or honesty) might be important aims for scientists. If used to choose between two competing theories, for example, "aims" might even be expressed as "methodological rules," another category of the cognitive-epistemic dimension of FRA (Erduran & Dagher, 2014; Irzik & Nola, 2011, 2014).

Values can serve direct roles (that is, as reasons for choices) or indirect roles (used to assess the sufficiency of evidence) (Douglas, 2015). Values can even be attributed to scientific objects (physical or symbolic) with which scientists are involved (Lykknes & Van Tiggelen, 2019; Pulkkinen, 2019). Cognitive values might typically provide information that can be used to assess usefulness and include complexity, simplicity, completeness, explanatory power, and predictability, while epistemic values might be used to assess credibility and encompass empiricist criteria, such as accuracy, robustness, consistency, testability, repeatability, viability, and novelty (Allchin, 1999; Chang, 2012; Douglas, 2015; Erduran & Dagher, 2014, pp. 41–65; Hadorn, 2018; Irzik & Nola, 2014; Pulkkinen, 2020). There is another group of values commonly labeled as "social values" (denoted as "institutional imperatives" by Allchin, 1999), which includes other values, such as honesty, inductive bias, and decentralization of power (Kelly & Erduran, 2019), as well as Merton's (1942) four idealized norms in science, that is, communism, universalism, disinterestedness, and organized skepticism. In Erduran and Dagher's (2014) extended version of Irzik and Nola's (2011) FRA framework, "aims and values" appear as a category in two out of three dimensions. In the cognitive-epistemic dimension, "aims and values" refers to the cognitive-epistemic goals of science that govern how and which activities are performed to reach them, and they are similar to the cognitive and epistemic values mentioned above. The commonly labeled "social values" resembles the "social values" category in the social-institutional dimension of FRA. Although the distinction between cognitive and social values is clearly artificial, the connectedness between categories is regarded as one of the strengths of the FRA framework (Cheung & Erduran, 2022).

Kelly and Erduran (2019) posited that valuing both the cognitive-epistemic and the social-institutional values of science is necessary for students to be scientifically literate. They further pointed to a scarcity in research about aims and values in science related to curriculum analysis and a lack of explicit focus on aims and values in science teacher education. In a recent study of the Norwegian science curriculum, Mork et al. (2022) found a strong emphasis on social values relative to curricula in other countries. They attributed this to an orientation to NOS in the Norwegian curriculum that "takes the human element in science seriously" (Mork et al., 2022, p. 15). However, in a recent operationalization of the part of the Norwegian science curriculum that is most relevant to NOS (Haug et al., 2021) the aspect of "aims and values" in science is given very little attention. Together, these two studies suggest that social values have a prominent place in Norwegian science teaching, while cognitive-epistemic values, and aims, run the risk of being delegated to the background. We now turn to how we utilized the FRA category "aims and values" to develop a teaching unit on aims and values in science from a historical episode, and how this can bring aims and values in science to the foreground for students.

4 Layer 2: Teaching unit, Group Interviews, and Thematic Analysis

Layer two consists of a separate empirical study, performed alongside the hermeneutic spiral (see Fig. 1) and feeding into it. To gain insight from students into our inquiry, a teaching unit was developed and tried out, and it was followed by group interviews of the students, transcription of their statements, and a thematic analysis (Berntsen, 2021). In this section, we elaborate on the methodology for the empirical study.

The study took place in February 2021 and included a class of 21 students (11 girls and 10 boys) aged 17–18 years at a large Norwegian upper secondary school, where chemistry is an optional course in the second and third year. The class was chosen from the first author's network, and some of the students were known to her from sporadic teaching assignments. The teaching unit lasted for 90 min and was conducted face-to-face by the first author. The study was approved by the Norwegian Center for Research Data. In addition, the informed consent of the participating students was obtained, and measures were undertaken to ensure the anonymity of the participants.

Table 1 Brief description of the teaching unit. The three recorded group works (1, 2, 3) denoted in bold type

Element	Description
Introduction	The teacher introduced the concepts of measurements and measuring, in particular temperature, with explicit links to students' previous experience with measurements (specifically, titration). Students participated in a plenary discussion on measurements that was led by the teacher.
Setting the context: describing the 18th and 19th century struggles in making temperature measurements, in particular, the choice of thermometer fluid	The teacher introduced the challenges natural philosophers in the 18th and 19th century faced with the use of thermometers, with a focus on the choice of thermometer fluid. The students discussed questions that natural philosophers at the time were also engaged with. The terms "single value principle," "reliable results," "theoretical assumptions," and "comparability" were emphasized by the teacher.
Alcohol as thermometer fluid	The teacher introduced the French natural philosopher Jean-André De Luc (1727–1817), and explained that he assumed constant heat capacity was a function of temperature. The students evaluated the comparability of De Luc's measurement data for alcohol thermometers. **Group work 1: Discuss the comparability of alcohol thermometers based on De Luc's measurement data.**
Mercury as thermometer fluid	The teacher introduced Henri Victor Regnault (1810–1878). **Group work 2: Evaluate examples of Regnault's measurement data with mercury thermometers made of different types of glass. Compare it to the air thermometer and discuss its reliability and comparability (among other things).**
Air as thermometer fluid	**Group work 3: Evaluate examples of Regnault's measurement data for the air thermometer with particular focus on comparability, and determine whether the air thermometer showed the true temperature.**
Summary	The teacher summarized Regnault's work and prompted the students to respond to what they had learned. The teacher encouraged students to link these responses to NOS aspects such as "aims and values" based on the students' own analyses.

4.1 The Teaching unit

An overview of the developed teaching unit is provided in Table 1. After an introduction about measurements, in general, as a way of linking the theme to the students' recent lab experiences, the teacher provided an oral introduction about the problem with the thermometers at the time and the context in which Regnault's work took place. The choice of level of detail, or "suitable grain size" (de Berg, 2008a) of the historical narrative, is a challenging aspect of translating historical episodes to teaching units. The FRA category "aims and values" provided guidance with regard to the level of detail about the context that was necessary for students to respond meaningfully to prompts about aims and values.

With the orally presented narrative about Regnault and his contemporaries as a structuring element for the unit, through an interrupted narrative technique the students were given the opportunity for interpretation by engaging with measurement data that were provided through handouts. For each of the three thermometer fluids investigated by Regnault and the French natural philosopher Jean-André De Luc (1727–1817) before him, namely, mercury, air, and alcohol, the students were given a specific group task (Table 1)—to engage in how Regnault's aims and values influenced his scientific judgments about comparability. The intention was that Regnault's drive for accuracy, which can also be considered as a scientific value or aim, could be experienced by the pupils through his measurement data, for example, by observing how Regnault avoided rounding off digits. In the same way, through a display of samples of Regnault's amount and accuracy of data, the value of empirically validating claims in science could be illustrated (Erduran & Dagher, 2014, p. 42). Instead of stating Regnault's aims and values explicitly, the teaching unit provided context about Regnault and asked the students to formulate their thoughts on Regnault's aims and values, through evaluating historical data and reflecting on aims and values in the subsequent interview.

4.2 Data and Analysis

The data material consisted of group discussions during class (n = 13) as well as group interviews with students (n = 8), which were conducted 2 days after the teaching unit was implemented. A total of 50 min of group discussions (three discussions, mentioned in Table 1, of 5, 10 and 10 min each, with two random groups selected for each discussion) and 90 min of group interviews (three interviews of 30 min each) were audio recorded and transcribed by the first author. Group interviews were preferred over individual interviews, as these can help create an informal environment that was believed to help discussions develop among participants and contribute to wider responses (Cohen et al., 2011). Group interviews were also preferred as the students were from the same class and, therefore, were familiar with each other. The interview questions included "Which values do you think Regnault navigated during his work in the 19th century?" "What was Regnault's aim during his investigations?" and "How is the reliability of the results affected by Regnault´s aims and values?" The eight students who were interviewed were divided into three groups based on their tutor's recommendation. Six of these students were also part of one of the groups whose discussions were recorded. Selected excerpts from a total of six students are presented here. One of these students, Emilie, participated only in the interview, while the remaining students also partook in group discussions.

Thematic analysis of all the available statements (n = 13 for the discussions, and n = 8 for the interviews) was conducted by the first author through continuous discussion with the two other authors, using an inductive approach described by Tjora (2018). From an initial set of 327 codes and 37 code groups, nine final code groups were developed. Based on a back-and-forth strategy involving the codes, code groups, the data set, and the research questions, as described by Clarke and Braun (2014), three main themes emerged. These three themes were reviewed and refined by the three authors through several iterations: (1) research is about the finding out of things, (2) publishing is important to substantiate and develop knowledge, and (3) the history of science provides insights into what it is to do science (Berntsen, 2021).

In the final layer, for the purpose of the present study, we take only the first main theme, "research is about the finding out of things," back into the hermeneutic spiral. We used students' statements, along with insights from reading the literature (Fig. 1), further outwards to layer three—Developing our arguments based on interpretations of students' statements by using the literature in layer 1 and 2. In the following section, we will develop our threefold argument on how the historical episode, through the use of FRA, (1) invited students closer to and helped them identify with the human actor; (2) helped highlight the narrative and, thus, invited students into the historical episode; and (3) demonstrated complexity and provided context to support students' own construction of their understanding of NOS.

5 Layer 3: Bringing it all together by Development of Arguments

In this section, we bring together literature and data from layer 1 and 2, interpret them, and develop three arguments. For each argument, the students' statements are presented first, and this is followed by our interpretation in concert with the literature. Quotes are marked with "group discussion" and/or an interview group number (e.g., *I1*) and a sequential quote number (e.g., **Q1**) to indicate their location in the empirical study. Pseudonyms are used for all student names to ensure anonymity.

5.1 First Argument: The Historical Episode Brought Students Closer to the Human Actor and Helped them Identify with him

In the interview, students were asked to identify which aims and values Regnault navigated in his work. As mentioned earlier, the teacher had not explicitly connected the different principles in Regnault's scientific conduct with aims and values, although some values had been discussed as students brought them up in the summing up session. All the students stated that Regnault's aim was to find the best thermometer. Usefulness was identified as a value that could provide guidance with regard to what to search for or find out in the students' views, as exemplified by Linda's statement: "We [the natural philosophers in the 18th and 19th century] could use a thermometer, that is useful for us" (Linda, *I1*, **Q1**).

Some of the students also suggested that being the first to find out or publish was a factor that could have been an aim for Regnault. It is interesting to note how Kirsten reasoned about this in the interview. At first, she stated "maybe he was a little driven by being the first" (Kirsten, *I1*, **Q2**). Later, on rethinking, she reasoned that the aim of his investigations was to find a standard thermometer:

Also, since he published everything [all of his data], so that others didn't need to, or could choose to just use his data instead of re-doing it, means also that it wasn't necessarily super important for him to be the first, but that he just wanted it [the investigations] to take place. (Kirsten, *I1*, **Q3**)

Finally, she concluded that "it was perhaps about them wanting to find a standard thermometer then, that actually shows the true temperature" (Kirsten, I1, **Q4**). The quotes point at the social value of being first and discuss the cognitive value of usefulness. Further, they demonstrate the intertwining of usefulness as both a value and an aim (that is, usefulness was an aim in itself).

With regard to how the historical episode and the FRA framework invited students closer to the human actor, we would like to point out that the quotes **Q2**–**Q4** illustrate how Kirsten *relates to* or *identifies with* Regnault when she is trying to put herself in his situation. This depicts how inviting the students to assume Regnault's *perspective* motivated them and helped them "understand how scientists think and act" (Larison, 2018, p. 114). Indeed, several students in our study stated that they had become familiar with how scientists at the time were thinking, as evident from Matildes' statement.

> *That you can sort of listen to what the others thought about it, what you have not thought about yourself. You sort of think a bit first and then know how they [the natural philosophers in the 19th century] really did it right, and how they thought at that time. I think that was interesting.*
> (Matilde, *I1*, **Q5**)

By familiarizing themselves with the historical narrative, the students could relate to and identify with Regnault. Thus, his aims and values provided the students with an example they could draw from in their thinking. Indeed, context-rich historical narratives, such as the episode about Regnault, can be considered as *narrative data*, which can more easily build on students' empathy for the main character than traditional numerical chemical data tables without any context (Fjørtoft & Lai, 2020).

We believe that the historical narrative framed within the FRA category "aims and values" invited the students closer to the human actor, or in Emden's (2021, p. 1050) words, the "processor" of scientific inquiry. Indeed, analogous to Matilde's quote in **Q5**, Kirsten's reflection on Regnault's aims and values (**Q2–Q4**) resembles what Larison (2022, p. 230) terms *nearness* or *side-by-sidedness* with the scientist. Larison states that most people, including students, find more meaning in relationships with other people than in looking for causal explanations. The agency of the main actor, Regnault, was available to Kirsten and created a "we-relationship" that promoted engagement. In fact, Linda even used the word "we" when referring to the natural philosophers of the 18th and 19th century (**Q1**). These results can be considered as a response to Larison's (2022, p. 231) call for more "intersubjective saliency" in science education.

5.2 Second Argument: The Historical Episode Highlighted Narratives and Invited Students into the Examples

The excerpts below exemplify how the students discussed the content of the comparability principle, which was an important guide for Regnault's work:

> *If you are to measure the temperature of that water over there with two different…, two different thermometers, they must show the same. Because the temperature cannot change from one thermometer to the other*
> (Matilde, *I1*, **Q6**)

About the [measurement with the] air thermometer, the temperatures were very similar. This shows perhaps that it is pretty good to use an air thermometer, because it is pretty much more exact.
(Elise, *I2*, **Q7**)
Yes, that it is a thermometer that actually works in situations. And not. And probably also measure all of ... save those thermometers that not really worked and that showed different .... that showed different temperatures in the same situation. Yes, and difficult to navigate by.
(Emilie, *I3*, **Q8**)

In the quotes above, Matilde, Elise, and Emilie articulate that the temperature cannot change from one thermometer to another, that there needs to be "very similar" temperatures, and that thermometers should not show different results in the same situation. These statements are all variants of the first part of the comparability principle, and they seem to be referring to a form of accuracy. In other words, here, the students are discussing the meaning of accuracy as a cognitive value in science. That the students discussed the comparability principle based on its meaning, rather than its definition, suggests that the exercise promoted conceptual *depth* through a focus on "concept as a signature of meaning," which is different from conceptual *usefulness* (which refers to a concept as a "problem-solving tool") (de Berg, 2008b, p. 167). de Berg (2008b) advocates for more conceptual depth, or teaching for learning, and states that history is an important context for concepts. We believe that the FRA framework contributes to providing this context in that it points the students to the example *before* the NOS abstractions are revealed. In other words, the historical context is given first, and then questions about NOS aspects are provided. Students can, thus, enter the examples and then draw from their familiarization with the historical context to construct the meaning of the concept of comparability, which is a cognitive value in science.

do Nascimento Rocha and Gurgel (2017) found that both the consensus view (Lederman, 2007) and the FRA framework reduce NOS teaching to describing science; instead, more room should be provided for creativity, criticism, and dialogic inquiry. They recommend that teachers ask themselves "What can students do with what is being taught?" (do Nascimento Rocha & Gurgel, 2017, p. 415). We argue that by inviting the students into judgments of comparability by letting them examine Regnault's (and De Luc's) actual measurement data, they *do* instead of describe. This makes the FRA more akin to a highlighting frame than a list, as it leads students to perceive the *basic moves* (Emden, 2021) of actual scientists. Movement is central in narratives, and we would like to present a quote that illustrates this point. During the group activity, which involved interaction with the measurement data, the students observed that mercury thermometers made of different types of glass provided different temperature readings. One of the students, Bendik, reasoned about how one could achieve more similar temperature readings:

On, well, the mercury thermometer that, different types of glass then led to different types of measurements. And that means that... if you were to use mercury, you must have the same glass all the time. But it can be difficult, which makes one..... And it will lead one to conclude that mercury maybe isn't the best way to measure. Since the type of glass to contain influences the measurements.
(Bendik, *I2*, **Q9**)

In **Q9**, Bendik re-iterated Regnault's reasoning on how the mercury thermometer was limited by its dependency on the type of glass and, thus, was inferior to the air thermometer. His clear descriptions of the initial situation (wherein the thermometers showed different readings), the action required to resolve the situation (better glassware production technology, which was not available), and the resultant situation (mercury was found to be inferior to air as thermometer fluid) resemble a *re-enacting* (Klassen & Klassen, 2014) of the narrative of how Regnault used measurement data to discriminate between mercury and air as thermometer fluid. Bendik's engagement with Regnault's actions helped him grasp the coherence in the narrative and enabled him to explain its essence. Thus, the use of the FRA category "aims and values" in framing a historical episode leads students *into* the concepts and helps "highlight the narratives," i.e., by pointing in the direction in which the main character is heading.

5.3 Third Argument: The Historical Episode Demonstrated Complexity and Provided Context to Support Students' own Construction of Their Understanding of NOS

During the group work, a discussion between Kirsten and Linda, shown below, illustrates how the students described the valuing of *data*:

> Kirsten: *That you can justify it, what you have found out then, with kind of evidence. […] No, he does not have statistics, but …eh. I cannot find the word for it.*
> Linda: *That you have, yes, that, yes what we have said, that it is kind of that we have, that one can settle it because you have, you have done so much research on it. And you have, yes. You have found it out.*
> Kirsten: *One has data.*
> Linda: *Data. Yes, you have … results.*
> (Group discussion, *I1* members, **Q10**)

The valuing of data was further mentioned when some students stated that it was important not to just *assume* but, rather, to test during research. During the teaching unit, the teacher (first author) emphasized that the assumption of constant heat capacity as a function of temperature was a weakness in methods chosen by Jean-André De Luc, and how Regnault valued data that relied on fewer assumptions. Emilie made the following comment about this:

> *Then he [De Luc] assumed that, since the alcohol thermometer did not work, it was the mercury thermometer that was best. I imagine that since Regnault wanted to show that even though alcohol…, even though mercury was more exact then, than alcohol, it may not be the most exact, after all.*
> (Emilie, *I3*, **Q11**)

Several students recalled in the interviews that Regnault was reluctant to make assumptions and emphasized on how his work was based on facts. In **Q11**, Emilie reflects on how Regnault did not assume that the air thermometer showed the true temperature only because it showed higher comparability than the other alternatives. Some students specified that facts were established and proven after being subject to considerable research. Overall, they had grasped that Regnault valued data over theoretical assumptions.

We consider that **Q11**, which is about the value of testing over assumptions, and **Q10**, the dialogue between Kirsten and Linda about the value of data, point to the essence of post-Laplacian physics. That is, they echo the frustration of the natural philosophers of that time, after tedious but rather unfruitful theoretical derivations. The statements can be interpreted as the start of appreciation about the *minimalism* highly valued by Regnault and his contemporaries, symbolized by Chang (2004, p. 95) as tightening the circle—using the fewest possible number of uncertain hypotheses and assumptions and emphasizing experimental data. Mohan and Kelly (2020, p. 1097) introduced the term *nature of scientist* (NOSist) to make explicit the, often, tacit practices of "how NOS is taken up by individuals within scientific communities": that is, the nature of science as it is negotiated at the micro-sociological level, where the everyday practices of scientists take place in all its complexity and context. Newcomers enter a community of scientific practice and engage in intersubjective exchanges of knowledge and practices, and this engagement is termed NOSist. NOS, in turn, emerges at a higher timescale level, where multiple NOSists intersect. By applying this viewpoint, it can be interpreted that the example invited students into Regnault's micro-sociological NOSist level—the valuing of data over assumptions—and that the students' statements exhibited indications of students' constructing of an understanding of NOS from their interactions with Regnault and his contemporary researchers. This represents a shift in viewpoint from the collective to the individual (Mohan & Kelly, 2020), from distance to closeness. Through such an individual focus, Regnault's thoughts, actions, and emotions are discernible from the statements about how Regnault preferred hard facts (measurements) over assumptions, as (individual) historical accounts display explorers' actions, thoughts, and emotions (Cavicchi, 2008). For the students in this study, Regnault can be interpreted as a member of the "mixed choir of scientists" (Tala & Vesterinen, 2015, p. 440) that constitutes a representative ensemble of real scientists. Familiarization with especially one scientist—Regnault—and his aims and values enabled the students to identify the characteristic features of science at the time, that is, the valuing of data over theoretical derivations. Thus, they were able to co-construct their own NOS from NOSist gained through the rich and complex example provided.

6 Shell: Summing it up through "Let them Research *with*"

We have now presented our core—an immersion into the historical episode of Regnault's investigations into the choice of the best thermometer fluid, our operationalization of the NOS aspect "aims and values" through FRA, the empirical study, our interpretation of the results from one of the themes that emerged from the study in light of the chosen literature, and our three-fold argument (Fig. 1). In the final turn of the hermeneutic spiral, we invoke elements from the newly introduced "performative paradigm" to wrap up the study, by arguing that students should be given the opportunity to research *with* the historical character.

The performative paradigm values closeness, complexity, and movement (Østern et al., 2021), positioning the researcher close to the phenomena of interest, in this case, a historical scientist. Rather than assigning concepts or models to preexisting things and, thus, creating distance and representability, an activity cherished by chemists and chemistry educators, the performative paradigm invites the researcher to participate in and be entangled with the phenomenon itself (Østern et al., 2021). That is, it produces "becomings" instead of static items, such as numbers and overviews, which resemble the construction of the NOS understanding we argue for in this study. We posit that the performative paradigm, in our context, might encourage students to come closer to the phenomena or the historical scientist, to experience the complexity and human aspect of it, and to *research with* Regnault. Instead of viewing scientific apparatuses as static measuring devices, it might—from a socio-material view—be considered as a "dynamic re-configuring of the world" (Barad, 2003, p. 816), or an open-ended practice, where the apparatus itself becomes a phenomenon with associated intra-actions, such as how the apparatus is used, how it is combined with other apparatuses, and how it is modified to suit particular purposes (Barad, 2003, p. 817). Regnault and his apparatuses form a joint phenomenon, showing movement in the form of constant re-configurations and alternations toward the aim of finding the true temperature. Thus, instead of presenting the thermometer as a static product of science, we can show movement. Closeness, narrative, and NOS from NOSist are results of transforming historical episodes to NOS teaching units, and they let students research *with* historical characters. As a final remark, the shift from "research *on*" to "research *with*" also resonates with trends such as the shift from students' "learning *from*" to students' "learning *with*" visual representations (Tippett, 2016).

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Declarations

Competing interests No competing interests exist.

Ethics approval The study has been approved by the Norwegian Centre for Research Data (NSD).

Consent Written informed consent has been collected from all informants.

Data, materials and/or code availability The teaching material is available online (Norwegian version) at https://www.ntnu.no/web/ilu/naturvitenskapenes-egenart.

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