Educational reconstruction of nuclear astrophysics in a design-based research project

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(Received 4 November 2025; revised 20 May 2026; accepted 18 May 2026; published 12 August 2026; corrected 13 October 2026)

This paper presents the first iteration of development and classroom testing of *Stars and Elements*, a web-based learning resource for Norwegian upper secondary physics students focused on how heavy elements are produced in stars and neutron star mergers. Combining the model of educational reconstruction (MER) with the pedagogical link-making framework and design-based research (DBR), we identified core ideas to be communicated, reviewed the physics curriculum and research on student understanding and motivation, and formulated design hypotheses that guided development of a 90-min learning resource with animations, videos, interactive tasks, peer discussion, and teacher consolidation. Six classes (N = 120) participated; data comprised students' written responses to three open tasks, brief evaluations, and classroom observations. Most students could describe central concepts and processes concerning red giant stars and neutron star mergers as sites for heavy element production, notably the slow and rapid neutron capture processes, and many benefited from animations and varied task formats. Some displayed uncertain grasp of concepts such as fusion and beta decay. Nature of science (NoS) aspects concerning how physics knowledge is developed were found to be insufficiently represented. From these findings, we propose design principles for research-based learning resources on similar topics, including emphasizing explicit link-making across scales and prior knowledge, scaffolding for challenging nuclear concepts, multimodal visualizations, and explicit NoS focus. We argue that combining MER, link-making, and DBR is a promising approach for developing learning resources that reflect the frontiers of science while having a solid grounding in the classroom.

DOI: 10.1103/ybmb-vknr

I. INTRODUCTION

Most elements that compose our world were created during the life cycles of stars or through dramatic after-life stellar events. This article explores how students can learn about and be motivated by these processes.

The 2017 detection of gravitational waves and electromagnetic radiation from a neutron star merger [1] offered new insights into the formation of heavy elements [2,3]. This event, occurring 130 million light-years from Earth, initiated *multimessenger astronomy*, where multiple data sources from an astronomical event enhance scientific understanding.

How can students engage with such cutting-edge research in school science? While textbooks typically cover hydrogen fusion into helium in stars like our Sun, the formation of heavier elements during a star's later life stages is rarely emphasized. Specifically, the revelation that many heavy elements originate from neutron star mergers has yet to be widely incorporated into upper secondary physics curricula and textbooks.

This paper discusses the initial development and first iteration of classroom trials of a web-based learning resource for upper secondary physics students titled *Stars and Elements*. This resource is focused on heavy element nucleosynthesis and was developed by a team consisting of two physics education researchers, a nuclear astrophysicist, and a science education researcher and developer specialized in digital resources.

II. BACKGROUND AND AIMS

A. Educational context: Norwegian upper secondary school physics and the viten.no platform

Physics is an optional subject in years 12 and 13 of Norwegian upper secondary school. The physics 1 course (year 12) is taken by 12% of Norwegian 18-year-olds. The current national physics curriculum [4] includes *matter, space and time,* and *practices and ways of thinking in physics* [understood in science education research as

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aspects of the "nature of science," (NoS)] as two of four core elements. One of the competence aims is for students to describe "how elements are created as stars live, collide, and die."

Established in 1999, viten.no develops and publishes free, web-based learning units in natural sciences for secondary students [5]. Each unit uses a framing narrative to provide a relevant real-world context and to facilitate focus on NoS aspects. The science content is presented through animations, texts, videos, and figures. Throughout each unit, students engage in various activities, including multiple-choice questions, drag-and-drop tasks, peer discussions, and open-ended writing tasks, with written responses stored in an electronic workbook for teacher feedback. The units are developed in collaboration with relevant professional communities and through classroom testing.

B. Aims and research questions

With *Stars and Elements*, we aim to provide a freely available learning resource on viten.no about heavy element nucleosynthesis in stars and neutron star mergers. Additionally, we seek to provide insights into student understanding and motivation in this topic and offer design principles for how to create digital learning resources presenting current natural science research. Specifically, we demonstrate how the model of educational reconstruction (MER) [6], combined with pedagogical link-making [7] and a design-based research approach (DBR) [8,9], can serve as a theoretical and methodological framework for educational development in physics.

Using pedagogical link-making as a lens, we address the following research questions:

RQ1: How do students describe concepts and processes related to heavy element nucleosynthesis through their work with *Stars and Elements*?

RQ2: How do students describe their learning experiences and motivation from *Stars and Elements*?

RQ3: Combining theory and previous research with findings from RQ1 and RQ2, what design principles can be formulated for the development of learning resources with similar aims as *Stars and Elements*?

III. THEORETICAL AND METHODOLOGICAL FRAMEWORK

A. The model of educational reconstruction (MER)

MER is a framework for science education research and development proposed by Duit *et al.* [6]. This model can be represented as a triangle, with science content and student learning considerations (including preinstructional concepts, attitudes, and interests) forming the base, and the teaching and learning intervention at the apex (Fig. 1). Arrows represent the interactions between these elements, illustrating that science content and student learning considerations are interlinked and that the learning intervention needs to be informed by, and feeds information back to, the two baseline corners. The model highlights that science content cannot be unproblematically "simplified" for students but must be reconstructed for the target population. MER is grounded in a constructivist view of learning; we adopt a social constructivist approach [10].

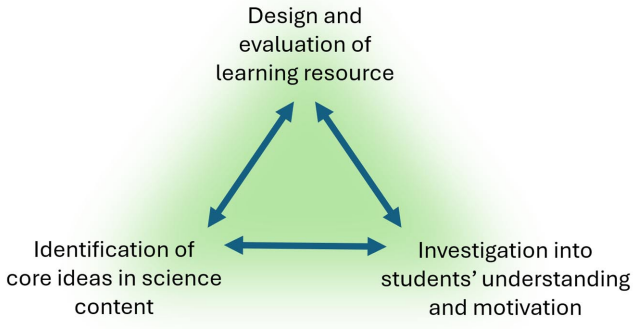


FIG. 1. The model of educational reconstruction, as interpreted for the purpose of this paper, based on Duit *et al.* [6].

We find MER particularly suited for developing instructional resources on topics with rapidly evolving research and no established teaching tradition, such as heavy element nucleosynthesis. Here, as opposed to, for instance, the case of Newtonian physics, scientific knowledge needs to be reconstructed for school purposes shortly following scientific breakthroughs such as the insights gained from the 2017 neutron star merger. The MER has previously been applied to content areas of current natural science research that are not widely represented in school physics textbooks, including nanotechnology [11], quantum science [12,13], and positron emission tomography [14]. Kersting *et al.* [15] combined MER with DBR to create a web-based learning environment on general relativity for upper secondary physics. This paper employs a similar approach to develop the resource on heavy element nucleosynthesis.

B. Pedagogical link-making

MER identifies central prerequisites for designing educational experiences for students, namely identifying the core ideas we want students to acquire and building on what is known about student understanding and motivation in the topic. However, MER provides few concrete recommendations on how to create an educational experience (in our case, an online learning environment) based on those insights. Scott *et al.* [7] described *pedagogical link-making* as a framework for how to support students' science learning process. With reference to constructivist and sociocultural views of learning, Scott *et al.* [7] described the main components of knowledge in science and how teaching should support students in linking these together. They suggested three main forms of link-making. *Link-making to support knowledge building* includes supporting (i) links between everyday and scientific ways of explaining; (ii) links between scientific concepts; (iii) links

between scientific explanations and real-world phenomena; (iv) links between modes of representation; (v) links between different scales and levels of explanation; and (vi) links between analogous cases. In *link-making to promote continuity*, the focus is on helping students develop their knowledge over time on the *macro* (months to years), *meso* (days to weeks), or *micro* (minutes to hours) scale. *Link-making to encourage emotional engagement* concerns helping students to engage in and be motivated for the learning process by creating memorable experiences that are intellectually relevant to students, developing their attitudes to science, and bringing together perspectives voiced by different students. In *Stars and Elements*, link-making has guided the educational design process and served as a lens for interpreting student understanding and learning challenges.

C. Design-based research (DBR)

DBR, also known as educational design research, aims to develop practical solutions for educational settings while gaining research insights into teaching and learning [8,9]. A DBR project involves an iterative cycle of developing an educational intervention (here: *Stars and Elements*), testing it in authentic settings (here: upper secondary physics classrooms), collecting data on student understanding and engagement, and revising the intervention before further testing. After a few iterations, the intervention is released for a wider target audience (here: made publicly available via viten.no), while the combined research and development insights often allow for transferable design principles to be published in the research field.

DBR is best viewed as a methodological framework rather than a singular research method, encompassing various specific approaches such as analyzing students' written or oral responses according to defined research aims (see Sec. V for methods in the present case). DBR synergizes with MER in emphasizing research-based development of educational interventions that consider both subject content and the learning context. MER, here combined with pedagogical link-making, provides a framework for reconstructing science content for educational purposes, while DBR offers a systematic method for developing learning resources based on iterative trials, generating research knowledge about student understanding throughout the process.

IV. AN EDUCATIONAL RECONSTRUCTION OF HEAVY ELEMENT NUCLEOSYNTHESIS

A. Identification of core ideas in heavy element nucleosynthesis

As outlined in Fig. 1, educational reconstruction in our case involved identifying the core ideas concerning heavy element nucleosynthesis that align with the curriculum's competence aim addressed by *Stars and Elements* (see Sec. II A).

The fusion processes that take place during the main series life cycle stage of stars cannot produce elements heavier than iron. The main processes that produce the heavier elements were identified by Burbidge *et al.* [16] and Cameron [17]. Here, we focus on the slow and the rapid neutron capture process (s- and r-processes). In both processes, nuclei capture neutrons and subsequently undergo beta decay, thereby gaining a proton and increasing their atomic number (i.e., changing into a heavier element).

Following the first discovery by Merrill [18] of technetium absorption lines in the electromagnetic spectrum of a red giant star, the s-process is known to take place in so-called asymptotic giant branch stars and very massive stars. In contrast, the astrophysical site for the r-process has been a subject of intense debate. For a long time, it was believed that violent star explosions such as core-collapse supernovae could provide the enormous neutron density needed for the r-process. However, simulations of supernovae made it clear that it is not possible to generate a sufficient density of neutrons in such events. The discovery that the neutron star merger in 2017 was accompanied by an "afterglow," i.e., an electromagnetic transient shifting from the blue region of the spectrum to the red and infrared frequencies within a couple of days, was finally a smoking gun showing that r-process nucleosynthesis did happen in the collision [2,3,19]. Whether neutron star mergers are the only source of r-process elements, or whether other rare events could have contributed in the early history of the universe, is a very active field of research today.

For *Stars and Elements*, the research group identified seven core ideas from the research area described above through internal discussion and review of research articles, popular accounts [20], textbooks, and encyclopedic entries. Table I presents the core ideas to be reconstructed in *Stars and Elements*.

B. Investigation into students' understanding and motivation relevant for learning about heavy element nucleosynthesis

In MER, previous research on students' understanding and motivation is central, as well as how curriculum requirements and educational contexts accommodate learning about the topic in question. Because heavy element nucleosynthesis is seldom taught at preuniversity levels and is a rapidly evolving research field, very little educational research was available. We therefore drew on research from relevant neighboring fields.

Students generally show strong interest in astrophysics and space [21,22]. However, they struggle with scale, distance, and temporal relations [23–25], and Rajpaul *et al.* [24] recommended visualizations and animations as tools for developing students' knowledge. Salimpour *et al.* [25] noted that many students struggled to correctly apply and reason with terms and concepts within cosmology. In a

TABLE I. Core ideas in heavy element nucleosynthesis identified as central content for *Stars and Elements*.

CI1	Stellar fusion cannot account for the formation of elements heavier than iron. Most of the heavy elements are formed in processes of neutron capture and beta decay.
CI2	The chart of nuclides is a central model for describing nuclear properties and processes.
CI3	The slow neutron capture (s-) process takes hundreds of thousands of years, occurs predominantly in a certain type of red giant star, requires smaller neutron densities than the r-process, and produces many of the elements between iron and lead.
CI4	The rapid neutron capture (r-) process takes seconds, occurs in neutron star mergers, requires orders of magnitude higher neutron densities than the s-process, and produces heavy elements such as gold and uranium.
CI5	A neutron star merger will produce gravitational waves as well as electromagnetic radiation, both of which may be detected on Earth.
CI6	The r-process formation of heavy elements will produce a characteristic fingerprint of electromagnetic radiation.
CI7	In multimessenger astronomy, different sources of information from an astronomical event, such as the 2017 neutron star merger, contribute to knowledge production.

sample of 17–18-year-old students, Bitzenbauer *et al.* [26] found that more than 40% believed that the Sun and our solar system were formed at the time of the Big Bang, and less than half of the students were aware that massive stars can evolve into neutron stars.

Research on nuclear physics education documents misconceptions about isotopes, nuclear stability, decay rates, half-life, and binding energy [27,28]. Kohnle *et al.* [29] observed that some students did not realize that beta decay involves that the nucleus increasing its atomic number. Moreover, some students thought that the emitted beta particle (electron) originated from the atom's orbiting electrons rather than from the nucleus.

The processes of heavy element nucleosynthesis are typically too small, too large, too extreme, or too distant for direct experience, which makes it challenging for students to link different scales and different modes of representation. Physics education research has shown that students struggle to reconcile macroscopic intuition with subatomic processes [30,31]. Some classroom interventions tackle this obstacle by using physical, interactive models—e.g., 3D nuclide-chart building blocks—to illustrate pathways for s- and r-processes [32–34], but these reports lack evidence on student learning or motivation.

The Norwegian physics curriculum emphasizes understanding the practices involved in physics as a scientific endeavor. Such NoS aspects are, however, often not prioritized or made explicit in teaching and in textbooks [35,36]. The 2017 neutron star merger is a strong, contemporary NoS example, illustrating how empirical evidence is used to build scientific knowledge.

Table II summarizes students' understanding, motivation, and challenges relevant for learning about heavy element nucleosynthesis.

The design of *Stars and Elements* was guided by pedagogical link-making and rooted in a social-constructivist view of learning. This means that students' prior ideas matter, active engagement is required, and social interaction and language are central to constructing understanding [10]. Effective learning mixes dialogic peer exploration with teacher-led authoritative consolidation [37]. Prior work with viten.no units on quantum physics found peer dialogue to be productive, with the authoritative role of the teacher important for consolidation [38]. These considerations align with pedagogical link-making, where learning requires linking concepts across representations and contexts [7]. For instance, a student may know what beta radiation is but still need support to link this understanding to what happens to the nucleus in beta decay and again link this to how new elements can be produced in the s- and r-processes.

Research also points to animations as powerful for dynamically representing processes across challenging

TABLE II. Relevant research findings on students' understanding and motivation.

RF1	Students are interested in learning about space and astrophysics.
RF2	Making links across space and time relations and between cosmic objects and events (for example, a 130 million light-year distance) is challenging for students.
RF3	Processing very large numbers such as neutron density in neutron stars is challenging for students.
RF4	Understanding that beta decay entails that the atomic number of the daughter nuclide increases, making it a different element, is challenging for students.
RF5	Understanding that stars and solar systems have been formed over generations in the history of the universe, rather than all in the Big Bang, is challenging for students.
RF6	Visualizing subatomic structures and processes is challenging for students.
RF7	Extracting knowledge of NoS from content-focused learning resources is challenging for students if NoS aspects are not made explicit.

TABLE III. Design hypotheses and associated opportunities for pedagogical link-making, for the first iteration of development of *Stars and Elements*.

Design hypothesis		Forms of link-making
DH1	Peer discussions will support students' learning of abstract core ideas related to nucleosynthesis.	Support knowledge building (links between science concepts and between science explanations and real-world phenomena); encourage emotional engagement (bringing together perspectives from different students)
DH2	Activation of existing understanding and explicit focus on key concepts will support students' learning of abstract core ideas related to nucleosynthesis.	Support knowledge building (links between scientific concepts); promote continuity on the mesoscale and macroscale (having students articulate understanding from previous learning experiences)
DH3	Animations and other visualizations of astrophysical and nuclear processes (e.g., neutron capture and beta decay) will support students' learning of nucleosynthesis.	Support knowledge building (links between modes of representation and between different scales and levels)
DH4	Comparisons with familiar objects will help students relate to and compare large scale distances, sizes, densities, etc.	Support knowledge building (links between analogous cases and between science explanations and real-world phenomena)
DH5	Tasks where students actively apply the newly presented subject matter will help them process their learning and connect new knowledge about heavy element nucleosynthesis to their existing physics knowledge.	Support knowledge building; promote continuity on the microscale, mesoscale, and macroscale
DH6	Teacher-led whole-class discussions will allow students to consolidate and reflect on their learning outcome while the teacher provides the authoritative view.	Support knowledge building; encourage emotional engagement; promote continuity (microscale)
DH7	Using a recent scientific discovery as a framing narrative, and including authentic pictures and graphs, will promote students' understanding of the nature of science.	Encourage emotional engagement (creating striking or memorable experiences and intellectual relevance)
DH8	Using an astronomical event like the 2017 neutron star merger as a framing narrative will promote students' interest in learning about nucleosynthesis.	Encourage emotional engagement (creating striking or memorable experiences and intellectual relevance)
DH9	Variation in types of tasks and use of multimodal content (text, images, videos, and animations) will support students' motivation and learning.	Support knowledge building (links between modes of representation); encourage emotional engagement

scales [39], supporting link-making across levels and forms of representation. Strømme and Mork [40] compared the performance of students working with animations or static visualizations of the protein synthesis in a unit on viten.no and found that students in the animated condition outperformed students in the static condition.

C. Design of a learning resource about heavy element nucleosynthesis

Based on the insights described in the previous sections and in line with MER, pedagogical link-making, and DBR, we formulated design hypotheses for how we expected different features of our design to support students' learning process (Table III).

A first version of *Stars and Elements* was developed by the research team and published with limited access on viten.no. Physics teachers and two nuclear physicists reviewed the resource before classroom trials, prompting minor refinements. The version that was tested in 2025 is described below, with reference to design hypotheses.

We assumed students to have the following background knowledge, allowing the unit to link new material to this knowledge to promote knowledge building and continuity:

1) how main sequence stars produce elements through fusion
2) the life cycles of stars and their end stages like neutron stars
3) atomic structure, the periodic table, and radioactivity, including beta decay
4) basic aspects of NoS, e.g., that science builds knowledge over time using empirical evidence

Based on the Norwegian physics curriculum, the core ideas (Table I) and research on students' understanding and motivation (Table II), we formulated learning goals specifying what we expected students to be able to do after working with *Stars and Elements* (Table IV). The unit is designed for about 90 min, a typical allotment for this topic.

These learning goals are introduced at the very start of the unit on viten.no. *Stars and Elements* uses multimodal content (videos, animations, text, and illustrations) and varied tasks (writing, peer discussion, multiple choice,

TABLE IV. Learning goals for a 90-min lesson working with *Stars and Elements*.

After completing this session, you should be able to	
LG1	Explain the concepts of *heavy elements* and *nuclides* and describe what a chart of nuclides is
LG2	Describe and compare nucleosynthesis through slow and rapid neutron capture
LG3	Describe how observations from a neutron star merger have provided new knowledge about where and how heavy elements are formed
LG4	Describe that most elements have been formed in stars that live, merge, or die, and give examples of elements that originate from different stellar processes and life cycle stages

drag-and-drop) (DH9). It opens with a 2-min video introducing the 2017 neutron star merger as a framing narrative (DH7, DH8). The video features a researcher in heavy element nucleosynthesis and shows visualization graphics from central publications about the merger event (Fig. 2) (DH7).

The first task is an open-ended prompt designed to activate prior knowledge and support link-making to previous learning experiences (DH2): "Where do you think the different elements on Earth come from? Write a few sentences." The unit then presents some concepts and processes related to nuclear physics and the lives of stars (DH2). Some are repetitions of subject matter the students have met in other contexts, such as *fusion* and *beta decay*, while others are new to them, such as the *chart of nuclides*. An animation of beta decay (DH3) involves a task where students actively engage with the subject matter (DH5) by filling in the new proton and nucleon numbers after beta decay of a cobalt nucleus (Fig. 3).

A short text points out that fusion cannot produce (substantive amounts of) elements heavier than iron, and slow neutron capture (s-process) is presented as a mechanism for producing elements between iron and lead. *Neutron capture* is highlighted as a key concept (DH2) and explained in a framed box. An s-process animation (Fig. 4) (DH3) shows nuclides moving steps to the right in the nuclide chart through neutron capture and then upward to the left in subsequent beta decay, ending with a stable cobalt isotope. It is asserted that this process takes place in a certain type of red giant stars over thousands of years. Students then answer three multiple choice questions on slow neutron capture to help them process the new content (DH5).

The next section is about rapid neutron capture (r-process). It explains that the s-process cannot produce all the elements heavier than iron, such as thorium and uranium, and that it only accounts for 1% of the gold in the universe. We then return to the 2017 neutron star merger framing narrative, pointing out that such a merger provides the necessary neutron density for nuclei to move quickly to the right and up the nuclide chart through a rapid succession of neutron captures followed by beta decays. An analogy compares the neutron density to the number of grains of sand on Earth compressed into a 1 cm^3 cube (DH4), supporting link-making with analogies with more familiar phenomena. An animation shows how rapid

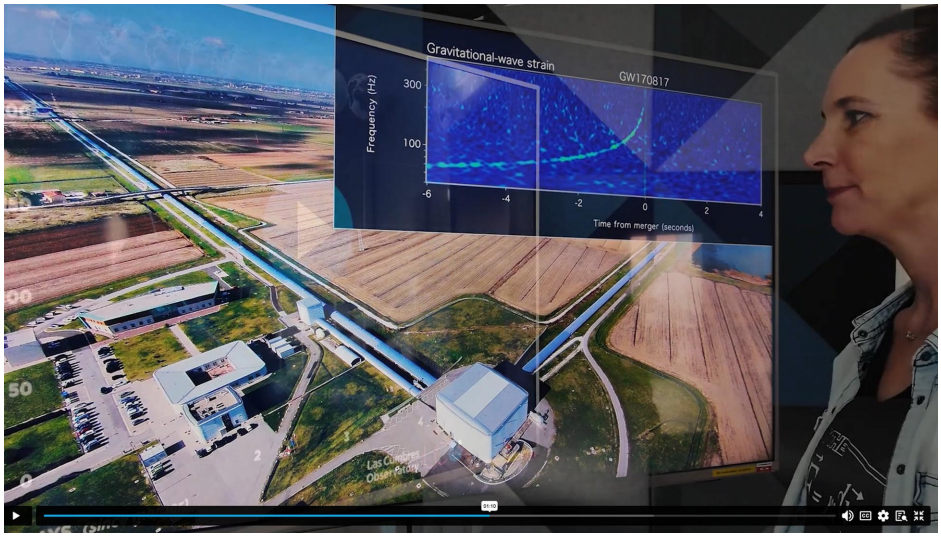


FIG. 2. Screenshot from the video in the beginning of *Stars and Elements*, showing a gravitational wave detector and the gravitational wave signal (Caltech/MIT/LIGO Lab).

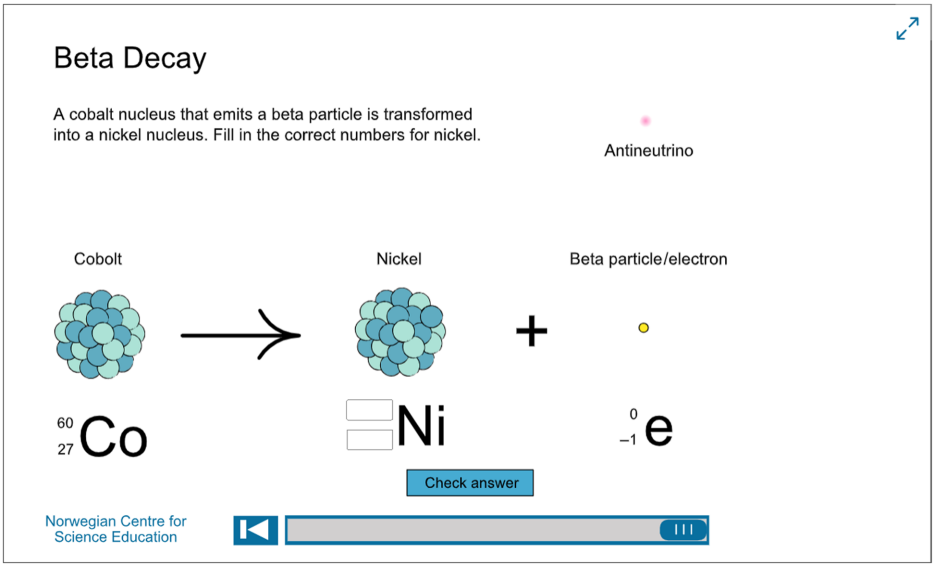


FIG. 3. An interactive animation showing the process of beta decay, asking students to fill in the nucleon and proton number of the daughter nuclide.

neutron captures and beta decays drive nuclides up the chart in seconds, leading to the production of gold. A peer discussion and writing task asks students to list similarities and differences between s- and r-processes, supporting knowledge building about these processes (DH1, DH5).

Stars and Elements then returns to the 2017 neutron star merger, presenting the central observations from the merger—gravitational waves, a gamma-ray burst, and the optical and infrared afterglow (DH8)—and how new knowledge was developed from it (Fig. 5).

Toward the end of the unit, an interactive task provides continuity links by bringing the focus back to the initial question of where the different elements originate from and lets students actively process and contextualize their knowledge (DH5). In the task, students drag-and-drop icons to assign origins to four elements (helium, carbon, barium, gold) on a periodic table scaffold (Fig. 6).

Stars and Elements concludes with a teacher-led whole-class discussion (DH6), offering an authoritative view of heavy element nucleosyntheses [37] and using a list of key concepts (neutron star mergers, red giant stars, slow and rapid neutron capture, beta decay, neutron density, fusion) to consolidate learning (DH2) and make links between scientific concepts.

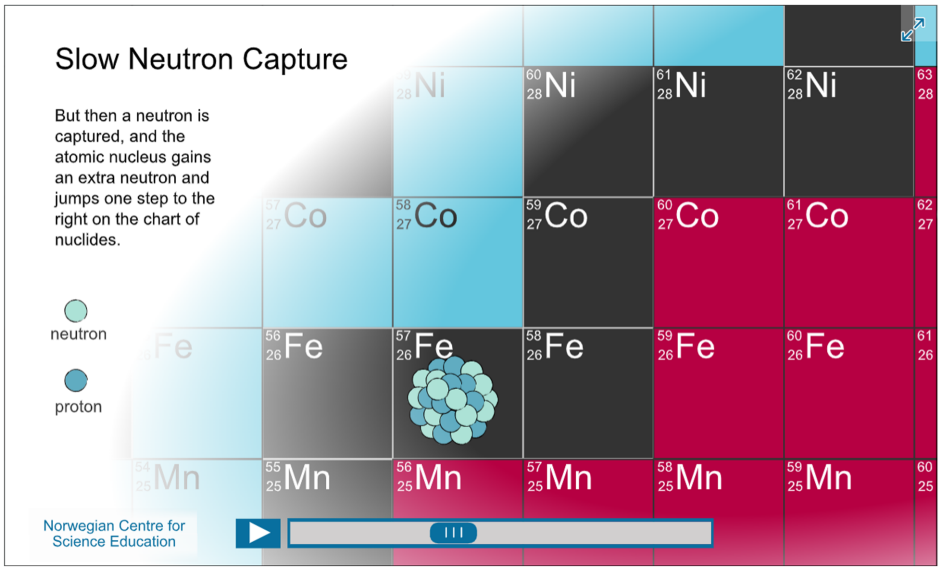


FIG. 4. Interactive animation of the slow neutron capture process; close-up of an area of the chart of nuclides.

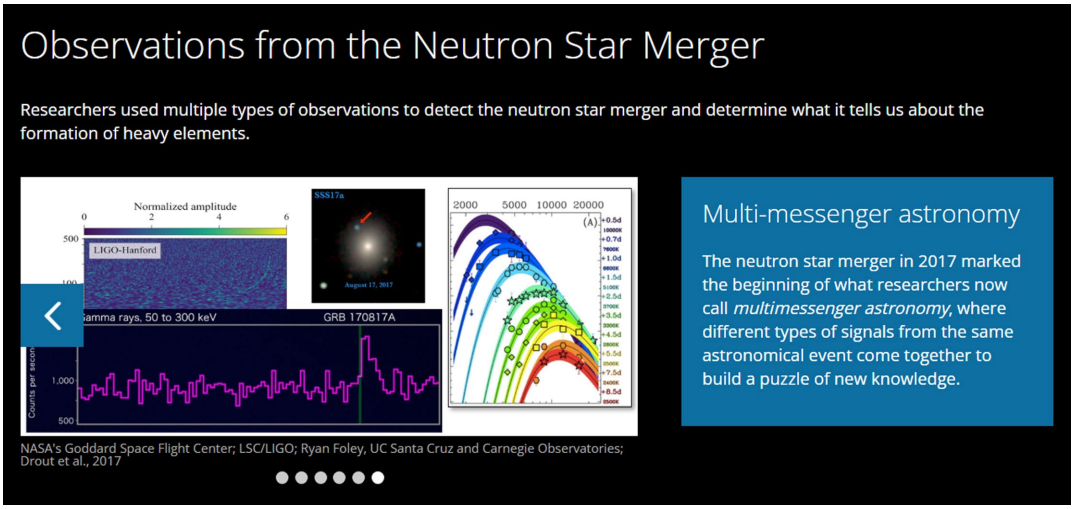


FIG. 5. A sequence of illustrations and texts presents the central observations from the 2017 neutronstar merger and their contributions to new scientific knowledge.

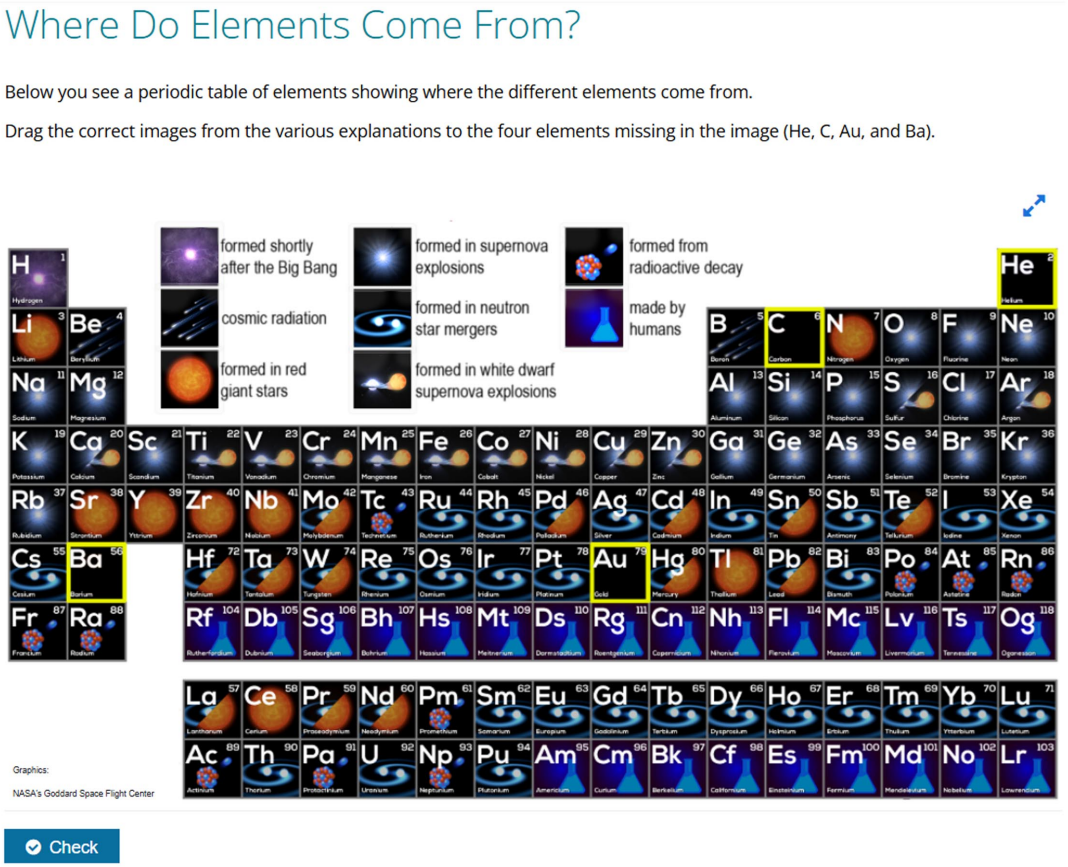


FIG. 6. Drag-and-drop task inviting students to fill in the origin of the four missing elements (marked with yellow frames).

V. CLASSROOM IMPLEMENTATION AND METHODS

A. Data collection and sample

Six upper secondary physics teachers in south-eastern Norway were recruited by personal contact to run the first classroom trials. Their six classes ($N = 120$; 46% girls and 54% boys) completed *Stars and Elements* on viten.no during a 2×45 min lesson and consented to participate. One or two physics educators from the research group attended each trial as participant observers. The regular

TABLE V. Overview of writing tasks (WT) and evaluation questions (Q) that provided the data material, and the number of student responses (out of 120 participants) for each.

Writing tasks (WT) and questions (Q)	No. of responses
WT1: Where do you think the different elements on Earth come from? Write a few sentences.	115
WT2: Discuss with a fellow student. What are the differences and similarities between the slow and rapid neutron capture processes? Then write down differences and similarities you can think of between the slow and rapid neutron capture processes.	103
WT3: Work with a fellow student. Imagine that you are going to explain to a lower secondary student where and how gold has been created. Discuss what you want to emphasize and how you will explain it. Then write down what you want to say to the lower secondary student.	83
Q1: Was there anything you found particularly interesting to learn about?	111
Q2: Was there anything you found particularly difficult or challenging?	107
Q3: How did you experience working with this viten.no unit?	110
Q4: I found the level of difficulty in this viten.no unit to be: far too low—somewhat too low—just right—somewhat too high—far too high	113
Q5: After working with this viten.no unit I have become more interested in learning about stars and the universe: compl. disagree—somewhat disagree—neutral—somewhat agree—compl. agree	113
Q6: After working with this viten.no unit I have become more interested in learning about nuclear physics: compl. disagree—somewhat disagree—neutral—somewhat agree—compl. agree	113

class teacher led each lesson, with observers offering clarifications and support.

Lessons began with the whole class viewing the introductory video. Students then worked in small groups while the teacher and researchers circulated, helping and observing. After each lesson, the researchers wrote brief observation notes focusing on student understanding and difficulties, possible resource revisions, timing, and the teacher's role.

The tested version of *Stars and Elements* included six evaluation questions at the end, covering overall experience, what students found interesting or challenging, perceived difficulty, and whether the unit increased their interest in nuclear physics or astrophysics.

Author 3 downloaded students' written responses from viten.no shortly after each trial, removed names, and assigned each student a number from 1–120.

The data used in this article consist of (i) written responses to three open writing tasks (WT1–WT3) and six evaluation questions (Q1–Q6) collected from 120 students in six classes (Table V), and (ii) the research team's classroom observation notes.

B. Data analysis

Students' written responses were analyzed to answer the research questions and to guide further development of *Stars and Elements*, and classroom observations were used to support the findings.

Responses to the closed questionnaire items (Q4–Q6) are presented using descriptive statistics. Responses to WT1–WT3 and Q1–Q3 were analyzed qualitatively using the NVivo software. The analytic approach is best described as directed content analysis [41], identifying prominent tendencies found in the data material. We examined students' descriptions of central concepts and processes of nucleosynthesis, and also their experiences with the resource, and how these supported or challenged our design hypotheses. In the coding of all qualitative data, patterns were viewed through the lens of pedagogical link-making. The unit of analysis was each full student response; multiple codes could be applied to a single response.

To address RQ1 about students' description of concepts and processes, author 1 analyzed WT1–WT3. Coding categories were informed by a related master's thesis and discussed with author 2. Coding was partly deductive—based on the core ideas (Table I), prior findings on student understanding and interest (Table II), and the learning goals (Table IV)—and partly inductive, based on respondents' actual expressions.

To answer RQ2 about students' description of their learning experience and motivation, author 2 analyzed Q1–Q3 using codes based on the design hypotheses (Table III). During the analysis, inductive codes were added to describe students' experiences not covered by existing codes (e.g., topics of interest or difficulty). Author 3 then went through the coding for validation purposes, and a few adjustments were made after discussions between the authors.

To answer RQ3 about design principles, results from RQ1 and RQ2 and experiences from classroom observations were compared with our design hypotheses in a discussion between authors 1–3. Specifically, we looked at evaluation questions Q1–Q6, where students were asked about interest, difficulty, and overall experiences working with the unit. Responses to these questions support general inferences about how well elements of the unit worked and were used together with the pedagogical link-making framework in the formulation of design principles.

C. Dual purposes of data collection and analyses

Because DBR combines design and research, the classroom trials had a dual aim: To help students reach learning goals in physics, and to collect data informing future development and the formulation of design principles. The various task formats used in *Stars and Elements* were chosen primarily to promote a varied and motivating learning experience. We do not have data on how, for instance, multiple-choice tasks, peer discussion, or teacher-facilitated consolidation contributed to students' understanding. However, although writing tasks WT1–WT3 were created primarily to promote learning rather than to serve as research instruments, we did use data from these tasks to gain information about students' conceptions.

VI. RESULTS AND DISCUSSION

In this section, coding categories identified as prominent in the analyzed material are indicated with *italics* and illustrated with quotes from the coded material. All student quotes were translated from Norwegian by the authors and are marked with respondent number (1–120).

A. Students' description of concepts and processes of heavy element nucleosynthesis expressed during work with Stars and Elements

The available data material that may contribute to answering RQ1 about students' descriptions of concepts and processes of nucleosyntheses consists of written responses to WT1–WT3 (see Table V). Below, patterns in students' responses to each of these writing tasks are presented and then discussed with reference to pedagogical link-making, core ideas, and learning goals where possible. In Sec. VI C, we show how these patterns contribute to the formulation of design principles.

1. WT1: "Where do you think the different elements on earth come from?"

WT1 was placed right after the introductory video presenting the neutron star merger and the scientific insights gained from it (Fig. 2). The task was designed to trigger students' interest and emotional engagement and to let them articulate their starting understanding, on which further knowledge could be built through link-making throughout the learning sequence. Responses to WT1 partly reflected the understanding students had before starting work with the unit and partly what they had picked up from the video. *Processes in stars* and *neutron star collisions* were the most prevalent categories, mentioned in roughly half of the responses:

> I think the various elements on Earth come from fusion processes in stars, and the heaviest elements come from neutron stars that collide. (20)

The *Big Bang* and *supernova explosions* were mentioned by a somewhat smaller proportion:

> They come from the Big Bang, origins of stars, fusion, stardust, and supernovae. (66)

Around one in ten responses expressed an understanding that the elements making up the Earth come from previous generations of stars. However, few described that the Earth was formed together with the rest of the solar system from material from earlier star generations; they focused on material "landing on" a (preexisting) Earth, for instance through meteorite impacts:

> I think the elements on Earth come from collisions between stars, and fall down on Earth by use of for example meteors (114)

A number of responses were very *general and imprecise* and demonstrated unclear or lacking links between concepts such as collisions, explosions and fusion:

> I think they come from space. Remnants of explosions of supernovae and other stars. At the same time, they come from the fusion of matter that originates from collision and explosion of earlier stars. (32)

Around one in four expressed explicit *misconceptions,* for instance

> I think they were formed because of the Big Bang collision. The collision was maybe a big chemical reaction that ended up creating all the elements. (107)

A handful seemed to mix up the words (or the concepts) fission and fusion:

> The lighter elements come from fission in stars, while the heavier ones come from large cosmic objects that collide. (59)

Overall, responses to WT1 indicated that students started *Stars and elements* with fragmented understanding of concepts and processes related to nucleosynthesis and that many displayed insufficient links between these concepts and processes.

2. WT2: "What are the differences and similarities between the slow and rapid neutron capture processes?"

On WT2, students' descriptions of the s- and the r-processes generally included the most important concepts and processes, which was to be expected since these were described very explicitly in *Stars and Elements*. Regarding

similarities, the most frequent aspect, explicitly described in around half of the responses, was that both processes involve *neutron capture* and *beta decay*, whereas somewhat fewer students observed that both lead to production of *new or heavier elements*.

> Both result in the formation of heavier elements. This happens through neutron capture, which causes the isotopes to undergo beta decay and form heavier elements (…) (6)

Regarding *differences*, the most frequently mentioned aspect was the *difference in speed* (slow versus rapid), mentioned in more than four out of five responses, followed by remarks about *where the processes take place* (in red giant stars versus in neutron star mergers) and *which elements are formed* (elements up to lead versus heavier elements such as gold). Around one in four responses mentioned *neutron density*:

> (…) In rapid neutron capture, the availability of neutrons is much greater, so the neutron capture and beta decays happen almost instantly. (91)

About one in ten responses referred to the nuclide chart, commenting on how the s- and the r-processes entail reactions in different regions of the chart and thereby demonstrating ability to link different concepts and forms of representation:

> (…) Slow neutron capture takes place near the stable, black nuclides in the middle. The process usually starts with nuclei of iron or nickel, while rapid neutron capture mostly occurs out to the right in the nuclide chart, where the nuclides have many neutrons. (62)

Roughly one in five responses contained *imprecise use of concepts* or outright *misconceptions*, for instance:

> (…) Rapid neutron capture takes place in supernovae and only takes a couple of seconds before the fusion is complete. (44)

As the above quote illustrates, a handful of students used the term *fusion* about heavy element nucleosynthesis. Also, some had trouble applying the concept of *beta decay*:

> (…) The similarities are that both emit beta decay, but the rapid one will emit more. (46)

We interpret these WT2 results to mean that most students had built knowledge about the s- and r-processes with helpful links between concepts (e.g., *neutron capture*, *beta decay*, and *heavy elements*) and representations (e.g., concepts and the nuclide chart), but that some students still struggled with imprecise conceptual understanding.

3. WT3: "Explain to a lower secondary student where and how gold has been created"

WT3 was placed toward the end of the unit, giving students a chance to sum up, in their own words, their newly built knowledge of heavy element nucleosynthesis after having worked with *Stars and Elements*, including several types of links made. Especially, this task provided an opportunity for students to link everyday with scientific ways of explaining. Here, the response rate was lower than for WT1 and WT2, see Table V. Based on classroom observations, we believe this to be because many found the task difficult and because it was late in the lesson and some students were running out of time or were tired. However, those who did respond, generally wrote longer texts than on WT1, and many of the texts were precise and reflected what had been communicated through the unit:

> Heavier elements like gold cannot be formed through fusion in stars, like the lighter ones can. When large stars die, they will become a neutron star. As the name suggests, there is a large surplus of neutrons in this star. When two neutron stars collide, the density of neutrons becomes high. An atomic nucleus can have several neutrons in it, as long as the protons is a given number. What happens is that such a nucleus captures so many neutrons (the density after the collision is high) that some of the neutrons are converted into protons. Thus, the atomic number goes up, and the element becomes a heavier element. This process is called beta decay. At the same time as the neutrons are converted, an electron is emitted. (11)

Three of four responses mentioned *neutron star mergers or collisions*, many linking these to the *r- and/or the s-process*:

> Gold is created in two different ways, slow neutron capture in red giant stars and rapid neutron capture after neutron star mergers. About 1% in slow neutron capture and the rest in rapid. (98)

Around 40% mentioned *beta decay*, often without explicit links to the actual concept:

> (…) When this happens, the existing lighter elements take in a lot of neutrons and convert them into protons, which changes the element down the periodic table until we eventually reach gold (Au). (75)

Thus, we note that even though beta decay is a challenge, many of our respondents were able to link the process meaningfully to nucleosynthesis toward the end of their work with *Stars and Elements*.

Among the WT3 responses, there were still around one in five that were *general and imprecise*, mentioning few concepts and few meaningful links:

> (…) When neutron stars collide, a lot of neutrons are shot around everywhere. These neutrons hit each other super sigma fast, and this creates a lot of new elements. (35)

Relatively few described all the central features in the formation of gold (neutron star merger resulting in gravitational waves and E/M radiation, high neutron density, rapid neutron capture followed by beta decay, resulting in heavier nuclides farther up along the chart of nuclides). Some mentioned *supernova explosions* as the only or main source of gold, although it was specified in the viten.no unit that supernovae can account for only around 1% of the gold in the universe. In WT3, like in WT1, around one in ten respondents linked nucleosynthesis in stars and neutron star mergers to the elements making up the Earth; however, some focused on these elements being brought to a (preexisting) Earth, rather than being part of the material that formed the solar system:

> Gold is made in explosions of supernovae and neutron star collisions. There, the atomic nuclei were bombarded with neutrons, formed gold and spread out into space before it landed on Earth (67)

The results on WT3 suggest that describing how gold is created was challenging for the students, possibly because it involves linking different concepts and processes presented throughout the unit and explaining in their own words including scientific and everyday language. Faltering descriptions of how gold created in a neutron star merger can become part of the Earth suggests insufficient pedagogical link-making in *Stars and elements* on spreading of elements in star evolution over generations.

4. Summary and discussion of students' description of core concepts and processes

To sum up students' description of core concepts and processes during work with *Stars and Elements* (RQ1), we have seen that toward the end of the unit, most students could express central aspects of how heavy elements are formed in processes of neutron capture followed by beta decay (CI1). They were also able to describe the slow and the rapid neutron capture processes (CI3 and CI4), and a few were able to link the chart of nuclides to their descriptions of how the s- and the r-processes proceed (CI2). These findings also indicate that students had attained LG1 and LG2, and that *Stars and elements* had provided pedagogical link-making toward those goals. However, many students displayed an incomplete grasp of central concepts such as *fusion*, *explosions,* and *beta decay*. These last findings corroborate earlier research results that nuclear physics concepts are challenging for students and that they often have a weak grasp of central concepts [28], particularly the process of beta decay [29].

CI5–CI7 and LG3 concerned signals received from the 2017 neutron star merger and how they were analyzed to give new scientific insights into heavy element formation. These CIs were to a very limited extent found in responses to WT1–WT3. This is not surprising, given that these core ideas are not explicitly asked for in the writing tasks (the ideas were, however, addressed through other task formats). However, we might anticipate that indications of students' understanding related to LG3 could be present in the responses to WT1 and WT3. This was not found to be the case; only one response to WT1–WT3 mentioned gravitational waves, and none specified electromagnetic waves, radiation, or light. This indicates that pedagogical links between descriptions of research breakthroughs (such as the observations from the 2017 neutron star merger) and general NoS ideas need to be more prominent and explicit in *Stars and Elements*, and writing tasks need to address these aspects directly, in line with recommendations that NoS content must be made explicit [36].

The fourth learning goal, LG4, aimed for students to understand that most of the elements that make up the Earth and everything around us have been made in processes involving previous generations of stars. This LG cannot be attained by working with *Stars and Elements* alone; it requires that the students have worked with fusion reactions and star life cycles beforehand. A small proportion of responses to both WT1 and WT3 touched on these aspects, mentioning for instance that our solar system was formed from material originating from previous generations of stars; however, students' formulations were faltering and contained misconceptions such as the notion that (most of) the elements were created in the Big Bang or that material from previous star generations mainly or only reaches us by means of meteorite impacts. This resonates with Bitzenbauer *et al.*'s [26] finding that some students believed that the Sun and our solar system were formed at the time of the Big Bang.

B. Students' descriptions of their learning experiences working with Stars and Elements

The six evaluation questions, three open-ended (Q1–Q3) and three closed (Q4–Q6), provided data about students' experiences of working with *Stars and Elements*. Collectively, they provide information about

- specific aspects that students found challenging and their opinion on the overall level of difficulty

- specific aspects that students found interesting, and to what extent *Stars and Elements* enhanced their interest in learning about nuclear or astrophysics
- students' overall experience of working with *Stars and Elements*, including support or challenge of some of our design hypotheses and the opportunities for link-making provided in the unit

Below we present the results on these three points. In Sec. VI C, we describe how these results contribute to our formulation of design principles.

1. What students found challenging in Stars and Elements

The closed question Q4 asked students to evaluate the level of difficulty of *Stars and Elements*. The vast majority (84%) responded that the level was just right. However, there were some aspects that some students found challenging. Coding of responses to each of the two questions Q2 "Was there anything you found particularly difficult or challenging?" and Q3 "How did you experience working with this viten.no unit?" identified around ten mentions of each of the following as difficult: *neutron capture*, *periodic table task*, *text and concepts*, *visualizations*, and *beta decay*. Additional data from classroom observations support that beta decay and the periodic table task (Fig. 6) were particularly challenging, as they generated many questions. One student wrote:

> I wish beta radiation was explained a bit simpler and clearer. Also, that the term beta radiation was used, because I think many more are familiar with this concept. (39)

This quote illustrates an important point, that the concept beta *decay* was used rather than beta *radiation*, which more students were familiar with from previous science education. Although we used decay deliberately to shift the focus from the emitted radiation toward what happens to the nucleus, *Stars and elements* did not sufficiently provide pedagogical link-making between what happens in the nucleus during beta decay and what they previously knew about emitted beta particles (beta radiation).

About the periodic table task, another student wrote:

> The task where we were supposed to find out which elements were formed in what way was a little difficult, and it lacked some context. (60)

The lack of context seemed to be particularly related to elements formed in fusion processes, which were regarded as previous knowledge and just briefly mentioned in *Stars and Elements*. Here, students did not appear to have the necessary resources for making links on the mesoscale and macroscale between (expected) previous learning about stellar processes and the new concepts presented in *Stars and Elements*. These results suggest that the unit should include more materials on fusion processes, providing students with better support to reach the curriculum competence aim saying that students should know "how elements are created as stars live, collide, and die."

2. What students found interesting in Stars and Elements

Responses to the closed questions Q5 and Q6 show that a clear majority of students agreed partly or strongly that working with *Stars and Elements* had made them more interested in learning about *nuclear physics* (61%) or *stars and the universe* (79%). This corroborates earlier research saying that the universe is a topic of great interest to students.

Some of this positivity could be attributed to novelty effect [42]; however, the impression that *Stars and Elements* had supported students' emotional engagement was strengthened by the fact that about a third of the respondents used words like *fun*, *exciting*, *cool*, and *interesting* to describe their overall experiences working with the unit in responses to Q3.

When asked if there was anything they found particularly interesting to learn about (Q1), students mentioned *the origin of elements*, *neutron capture*, and *neutron stars and mergers* most often (43, 32, and 18 times, respectively). One student wrote about all three aspects:

> It was interesting to learn about neutron stars; they are exciting phenomena. It was also interesting to learn about nuclides and how heavy and lighter elements can be formed through fusion and neutron collection. (70)

3. Support or challenge of our design hypotheses and use of pedagogical link-making

Stars and Elements was designed to provide pedagogical link-making to support student learning of heavy element nucleosynthesis and promote their interest in related topics to motivate engagement in learning. These goals and the literature review presented in Sec. IV B led to the design hypotheses (DHs) given in Table III. Although the data from this first iteration do not allow us to fully confirm or reject all DHs, the analyses found support for some DHs and challenge of others.

First, based on students' self-reports, *Stars and Elements* seems to have helped students learn. When asked about their overall experience of working with *Stars and Elements* (Q3), more than a third of students responded with formulations that mean it was helpful for learning.

> It was fun, and I learned a lot that I didn't know before. (25)

This quote also illustrates that the learning experience was emotionally engaging and personally relevant, in line with pedagogical link-making.

The results support DH3 about learning from animations, linking forms of representation and levels of explanation. Although the questions did not explicitly mention animations or visualizations, these were described positively by students 21 times in responses to Q1–Q3.

> I felt that it was quite easy to learn compared to just reading a book. I especially liked those animations. The fact that there were visual elements that changed [to show] what was happening made it easier for me to understand. (64)

There was also support for DH9 about variation in task type and use of multimodal content. One in seven student responses were coded in this category:

> It was very instructive, and the program worked well. There was a nice variation between different elements like text, interactive videos, and carousels. (…) (93)

> Pretty good. Variation is good, and I got to practice explaining concepts. (9)

The latter quote also explicitly mentions concepts, which are emphasized in *Stars and Elements* as reflected in DH2. These quotes suggest that *Stars and Elements* provided opportunities for students to make links between scientific concepts and forms of representation.

DH8 stated that "Using an astronomical event like the 2017 neutron star merger as a framing narrative will promote students' interest in learning about nucleosynthesis". The overall results support this design hypothesis. As reported above, a large proportion of students agreed that *Stars and Elements* had made them more interested in learning about both nuclear physics and stars and the universe, and 18 of them explicitly mentioned neutron stars as an interesting element in Q2, again showing that *Stars and Elements* provided opportunities for emotional engagement:

> I found it especially interesting that researchers thought rapid neutron capture happened in supernovae until they found out in 2017 that it occurs in neutron star collisions. (95)

This quote also points to the significance of the recent neutron star merger for knowledge development in nuclear physics, suggesting some gained insight into NoS. However, this was one of only a handful of quotes that reflected such insights. There were even a couple of students who wrote that NoS aspects were difficult:

> Understanding how researchers discovered neutron star collisions, with gravitational waves and gamma radiation. (75)

Therefore, we cannot at this point conclude whether using a recent scientific discovery in the unit helps students understand NoS aspects (DH7). Based on the literature [36], NoS aspects should probably be more explicitly pedagogically linked to the rest of the content in *Stars and Elements* to promote NoS learning. Moreover, more explicit investigations into student learning of NoS aspects are needed in future iterations to evaluate DH7.

Other design hypotheses also require more investigation in future iterations of the DBR process. That applies to DH4 about helping students relate to and compare large scale distances, sizes, densities, and DH5 about using tasks throughout to help students process learning in this topic. Yet other design hypotheses reflect more general, well-documented knowledge in science education, such as the value of peer discussions (DH1) or whole class teacher consolidation (DH6) and can be used without more explicit evidence.

4. Summing up how students described their experiences working with Stars and Elements

To sum up the results that answer RQ2, a clear majority of students described the level of difficulty in *Stars and Elements* as "just right." However, new concepts and processes such as *neutron capture*, *beta decay*, and the *periodic table task* were found to be challenging and require better pedagogical link-making. Microscopic processes and concepts are known to be difficult to grasp in general [30,31], and in nuclear physics, previous research has documented struggles with beta decay [29], which were also found in our case. However, most students agreed that *Stars and Elements* made them interested in learning more about nuclear and astrophysics, and *the origin of elements*, *neutron capture*, and *neutron stars and mergers* were often mentioned as interesting aspects. The interest in astrophysics was expected from the literature [22] and may have influenced a broader interest and emotional engagement in nucleosynthesis. Many students described *Stars and Elements* as helpful for learning, and the use of animations [24], variations in task type, and the 2017 neutron star merger as a frame appear successful. However, NoS aspects need to be made more explicit, and inclusion of learning materials on the formation of elements in fusion processes appears necessary to give students a better overall understanding of the origin of elements, offering extended opportunities for pedagogical link-making to promote continuity and support knowledge building.

C. Design principles

In design-based research, outcomes may be formulated in the form of design principles, also known as design

frameworks [15,43]. We have developed a set of design principles that are partly based on theoretical frameworks and previous research, as expressed in Secs. III and IV of this article and summarized as design hypotheses in Table III, and partly on our empirical findings, presented in Secs. VI A and VI B. These principles (Table VI) guide the next round of development of *Stars and Elements*, but more importantly, they may be useful for those developing and researching learning resources for similar groups of students (secondary school to undergraduate university education) about similar topics (notably topics within nuclear physics and astrophysics and other topics that are not represented in mainstream textbooks for the target group). The table presents general design principles and central implications for *Stars and Elements*, including features that appear to have been useful in the first iteration as well as features that will be changed in the next iteration.

Comparing these design principles with those arrived at in related publications using DBR to develop physics learning material, we find some commonalities. For instance, Kersting *et al.*'s [15] principle 2 about linking key concepts to students' lifeworld, notably by use of simulations and animations, resonate with our DP1–DP3, and their principle 3 about drawing on students' motivation and interest, notably in astronomical phenomena, aligns with our DP4. Two publications on educational reconstruction of quantum technology [12,13] did not state explicit design principles and differed from the present project in taking a more mathematics-based and formalistic approach. Still, they displayed similarities with our design principles for

TABLE VI. Design principles for learning resources about nuclear and astrophysics for upper secondary physics students, based on findings from the first iteration of the development of *Stars and Elements*.

	General design principle	Implications for *Stars and Elements*
DP1	Provide explicit links for knowledge building between important concepts and processes, including continuity links to students' previous knowledge (macroscale to mesoscale), and links within the resource (microscale)	Provide better support for students to link previous knowledge of beta radiation to beta decay, and to separate fusion from fission Provide better support for students to link previous knowledge of stellar life cycles to processes of nucleosynthesis Extend *Stars and Element*s with a new module on fusion processes that produce the elements up to iron, allowing students to build a more complete knowledge overview of the ways in which elements are produced in different star life cycle stages and cosmic events and how these elements became part of the Earth
DP2	Provide writing and discussion tasks that require students to actively use new concepts and link them to each other, to scientific explanations of phenomena, and to students' everyday experiences	Improve and expand writing and discussion tasks designed to scaffold students' knowledge building about how and where the elements they know (e.g., gold and uranium) are created.
DP3	Use animations and other visualizations to support link-making between different scales, modes of representation, and analogies.	Use animations and visualizations of nucleosynthesis concepts and processes also when extending the learning resource to include fusion processes in stars, e.g., animations using the chart of nuclides
DP4	Link new content to topic areas with documented high student interest to encourage emotional engagement	Include images and videos using astrophysics as an entrance to nucleosynthesis also when extending the learning resource to include fusion processes in stars
DP5	Provide task variation and multimodal content (text, images, graphic descriptions, videos, and animations) to support emotional engagement for different students and help students consolidate learning	Provide task variation also when extending the learning resource to include fusion processes in stars
DP6	Provide explicit links between general aspects of the nature of science (NoS) and the NoS aspects represented in the specific examples in the learning resource	Make NoS aspects in the framing narrative of the 2017 neutron star merger and its impact on physics knowledge more explicit Use a framing narrative with explicit NoS aspects also when extending the learning resource to include fusion processes in stars
DP7	Use peer discussions and teacher-led whole-class discussions to promote knowledge building and emotional engagement by bringing together perspectives from different students and to ensure authoritative as well as dialogic communication forms [37]	Use peer discussions and teacher-led whole-class discussions also when extending the learning resource to include fusion processes in stars

instance in emphasizing representations [12,13] cf. our DP3, and in attention to the cultural significance of scientific breakthroughs for knowledge building [12], cf. our DP6. Chatzidaki *et al.* [14] stated design principles based on analysis of an already developed digital learning module on positron emission tomography, in combination with relevant theory and findings from the research literature. Their design principles display commonalities with ours, for instance regarding contextualizing the learning resource using topics with documented student interest (cf. our DP4), promoting "generative learning activities" using activity prompts (cf. our DP2), and taking advantage of the affordances of multiple representations, including multimedia and animations (cf. our DP3 and DP5).

D. Limitations

This study was conducted with 120 students and 6 teachers in the south-eastern part of Norway, and these participants are not necessarily representative of upper secondary physics students and teachers—in Norway or elsewhere. That said, tendencies identified in our sample are likely to be present also in comparable populations of students. Also, since we do not have data from the closed-ended tasks or from peer discussions or teacher consolidation, and since the open-ended writing tasks were designed for learning purposes rather than for research, our data do not offer insights about all aspects of students' interaction with the learning resource, nor do they allow us to conclude concerning all parts of students' understanding and motivation within the topics concerned. Therefore, we limit our conclusions to those that are supported by broad, robust patterns in the data. Finally, the present article reports only from the first iteration of a design-based research process. At the time of writing, *Stars and Elements* has been revised and extended with a module on fusion processes in stars, and a second round of classroom data has been collected but not yet analyzed.

VII. OUTLOOK AND CONCLUSION

We have described the first iteration in a process combining the model of educational reconstruction and design-based research to develop a web-based learning resource about heavy element nucleosynthesis aimed at Norwegian upper secondary physics students. This has involved transforming parts of the nuclear astrophysics research field into a content structure for instruction, as described by Duit *et al.* [6], using pedagogical link-making to guide the design process and taking advantage of the learning opportunities that digital formats offer [44]. Based on our research and the literature, we have proposed design principles for educational development on similar topics to upper secondary and undergraduate students.

Our research indicates that students can acquire understanding of how heavy elements are formed through working with a digital learning resource. However, as previous research [38] has underscored, digital resources like *Stars and elements* require an active teacher who can help students make links [7], answer questions and clear up misunderstandings, and provide the authoritative voice in consolidating discussions [37]. We have also presented evidence that such digital learning resources, when using a variation of formats and tasks, may encourage emotional engagement by supporting students' interest and motivation, thus enhancing learning [45]. As found in earlier research [36], we also conclude that NoS aspects must be treated explicitly to realize the potential for learning about NoS that is inherent in a MER process reconstructing content from an active research field for the classroom. Juuti and Lavonen [46] assert that "design-based research provides a novel artifact and novel knowledge highly interconnected with each other. Thus, they help researchers to improve teaching (…)." In line with this dual aim of DBR processes—to produce educational resources that are usable in real educational contexts and to produce knowledge of student understanding that teachers and researchers may use—our research and development process has resulted in four main contributions.

First, it has resulted in a learning resource that has, at the time of writing, been used by more than 300 students over two iterations and that will be further revised and eventually made freely available for use in education. Second, our empirical findings have highlighted some challenges of student understanding and learning within our topic area, such as their uncertain grasp of some central concepts and processes in nuclear physics and astrophysics, for instance, fission and fusion, beta decay, stellar explosions, and collisions. Our results also suggest that some students may struggle to link previous stellar and cosmic processes such as neutron star mergers and supernova explosions to formation of our own solar system and the elements that surround us. This adds to the very limited research base on student understanding of nuclear and astrophysical processes. Third, based on previous research, theoretical perspectives (notably the pedagogical link-making framework), and results from our classroom testing, we have offered a set of design principles (Table VI) that can be used for physics education projects with similar aims to ours and that specifically guide our next iterations of development of *Stars and Elements*. As our fourth and final contribution, the development process of *Stars and Elements* and the findings presented in this article illustrate how MER, pedagogical link-making, and DBR may be fruitfully combined to reconstruct and present a current area of natural science research to a target group of learners.

VIII. ETHICAL STATEMENT

All data used in this paper have been collected and stored in accordance with the data protection guidelines of the Norwegian Agency for Shared Services in Education and

Research, SIKT (ref. no. 152462). All participants consented to take part.

ACKNOWLEDGMENTS

We would like to thank physics teachers and students for their participation and master's student Helene Aune for her contributions to data collection and initial analysis. Partial financial support was received through a grant to the Norwegian Nuclear Research Centre from the Research Council of Norway (Project No. 341985).

All authors contributed to the study conception and design. Natural science expertise: A.-C. L. Educational web design and science education research expertise: Ø. S. Physics education research expertise: E. K. H. and M. V. B. Data collection and analysis: M. V. B., Ø. S., and E. K. H. Manuscript preparation: Led by E. K. H. and M. V. B., with contributions from Ø. S. and A.-C. L. All authors read and approved the final manuscript.

On behalf of all authors, the corresponding author states that there is no conflict of interest.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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Correction: In the Introduction and in Table II, the reference to light-years was missing the word "million" and has been rectified (it now reads 130 million light-years).