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Beyond Problem Solving: Designing Concept-Building Worked Examples for Chemistry Education

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ABSTRACT

Science teaching in schools attends to two major varieties of knowledge: procedural and conceptual. While studies on how to support procedural learning in science have abounded over the past two decades, the situation regarding conceptual learning has been markedly calmer. Yet, as conceptual learning is a necessary requisite for any learning, viable methods to support students in their learning are needed. The present article reviews two approaches to conceptual learning from texts—expository and refutation—to identify potential. It merges these findings with research on learning with worked examples to suggest the design of an innovative format of learning materials: concept-building worked examples. A set of these is designed relying on the Cognitive Theory of Multimedia Learning, while capitalizing on suggestions from research on learning with texts. These concept-building worked examples allow students to develop scientific concepts at their own pace—something hardly accomplished by traditional textbooks. The materials are meant to be used for self-study. They have been published online free of charge. Overall, 34 concept-building examples help students in lower secondary education (ISCED-level 2) learn nine chemical concepts. These concepts are developed stepwise in narrative texts between characters that students can identify with. The worked examples introduce expert and lay characters, where the latter serve as stand-ins for students sharing the character's preconcepts and allow for an explicit take-up of these. Self-explanation prompts and concept-related tasks ensure active processing of the worked examples' content. Illustrative examples are provided to renew discourse on concept-learning in chemical education.

Keywords: chemistry education, concept-learning, worked examples, refutation text, learning from text

Introduction

Recent science education has devoted an extended focus on domain-specific problem-solving abilities, be it in the form of scientific inquiry (National Research Council [NRC], 1996) or in the form of scientific and engineering practices (NRC, 2011). This development is mirrored internationally in curricula, and much research has addressed novel and improved ways to facilitate student growth in their respective problem-solving abilities. One argument for this emphasis on "doing science"—as opposed to, *e.g.*, "knowing science" (Hodson, 2014)—is that the conceptual knowledge base of science is expanding more rapidly than schools could ever manage to accommodate within their limited syllabi. Therefore, the idea is to introduce students to prototypical ways of thinking and acting in science, as this could empower them to generate their own scientific knowledge as well as to reflect on how authentic science generates its knowledge.

Science education has come to orient itself towards three visions of scientific literacy with different emphases: Vision I scientific literacy might be termed the "vocational approach" enabling students to take up science related work or studies after school; Vision II scientific literacy is a "pragmatic approach" that wants students to realize where science features helpfully in their everyday lives (both: Roberts, 2007; Roberts & Bybee, 2014); Vision III scientific literacy acknowledges that modern societies are dependent on scientific resources, so that members of these societies need to have command over some "democratic scientific literacy" that allows them to evaluate and choose between several solution suggestions, to distinguish fake news from real ones, and to identify deliberate disinformation concerning scientific facts (Sjöström & Eilks, 2018). Each of these visions relies on conceptual scientific knowledge that students are expected to master. While much work has been done in the past decades on supporting students' progress in the processes of science, it appears as if it has been missed to some degree that science is an extremely theory-laden endeavor (Lederman, 2007). Students cannot rely solely on being introduced to "doing science," but their enactment of science needs to fall back on a conceptual basis, *i.e.*, they need to "know science", too. Klahr and Dunbar (1988) have shown in their Scientific Discovery as Dual Search approach that the generation of knowledge necessarily draws on available conceptual (search hypothesis space) and procedural knowledges (search experiment space). If either of these knowledges is atrophied or non-existent, there can be no scientific discovery.

So, while teachers and science educators are laudably turning towards a flexibilization of science literacy by emphasizing exemplary and transferable procedural abilities and skills, they must not overlook the likewise essential task to lay conceptual foundations on which these abilities can work (see also Sinatra & Broughton, 2011). The present article aims to introduce an innovative task format that is devoted to achieving conceptual change at students' pace. The development of self-learning materials is considered to be a crucial element in contemporary chemistry education, which is chronically short of time and faces challenges of cumulative learning as few other school subjects do. Disregarding student needs or barring them from catching up on their own will leave many students stranded when it comes to matters of scientific literacy. Developing self-learning materials is time-consuming and teachers cannot be expected to each take on this task—especially with regard to extensive sets of materials. Tested materials, therefore, need to be introduced in a way that science educators and teachers from other locales can adopt them (considerably) easily. The current article introduces such a set of tested materials for self-study of fundamental concepts in chemistry. It hopes to encourage colleagues from different contexts to identify potentials how to bring the materials into their classrooms, how to adopt them—*e.g.*, using artificial intelligence technologies—, or how to develop their own learning materials building on the same design principles.

The current article will therefore start by relating what we understand about how concepts are learned. It will, then, go on to discuss how concept-learning can be supported by learning with texts—it discusses learning from expository texts and refutation texts before turning to learning with worked examples. Each of these perspectives will contribute insight into learning concepts either as challenges or as potentials. These will be employed to design an innovative instructional text format supporting concept learning in chemistry at the lower secondary level (ISCED-level 2). Research findings on its effectiveness are briefly introduced, and perspectives for adoption of the worked examples are discussed.

Theoretical Background

The theoretical background will introduce relevant theory and research from science education on concept-learning, learning from texts, and learning from worked examples. It aims at highlighting the benefits and challenges of each approach regarding student learning. “Lessons learned” from these lines of research (Table 1) will serve to gauge hitherto unchanneled synergies and inform the design of an innovative format: concept-building worked examples.

Scientific Concepts in International Curricula

Most international curricula are oriented towards a limited number of crucial scientific concepts that need to be introduced. The NRC-standards (NRC, 2011) refer to these as (a) Core Ideas, *i.e.*, central domain-specific concepts (*e.g.*, evolution, chemical equilibrium), and (b) Crosscutting Concepts, *i.e.*, those concepts spanning scientific domains (*e.g.*, energy). Another example are German educational standards for chemistry education (KMK, 2024) that give these basic concepts: (1) composition and properties of matter and its particles, (2) chemical reaction, (3) energy changes. Within this framework, any chemical phenomenon can be approached from each of the three perspectives, which, in turn, can be further differentiated, *e.g.*, introducing donor-acceptor concepts in the scope of chemical reactions from the second basic concept.

Still, most international curricula specify—across these core ideas or basic concepts—more comprehensive canons of conceptual scientific knowledge that should be introduced (*e.g.*, atomic models, acid-base reactions, redox reactions). These topics form the backbone or narrative line for developing science classes in which students can also develop their procedural abilities. A major problem in this endeavor is that of too little classroom time—too frequently introductions by teachers need to move at a quicker pace than is beneficial for all the students (van Vorst, 2018). Some might even get lost and have little chance to find their way back by themselves. This could prove problematic in a subject such as chemistry, where understanding one concept often is prerequisite for learning a new one.

Concept-learning

Concepts can theoretically be described as mental representations of fundamental knowledge structures (Krajcik & Shin, 2023). One can distinguish between psychological concepts and cognitive concepts, where the former term relates to more subjective, intrapersonal mental representations and the latter to public, interpersonal representations (Gilbert & Watts, 1983; Rusanen & Pöyhönen, 2013). Formal education aims at developing students’ preexisting psychological concepts (*i.e.*, preconceptions) to align better with the consensual, definitory concepts held in a scientific discipline—the process for this development has been referred to as Conceptual Change for roughly the past four decades (Krajcik & Shin, 2023; Posner et al., 1982; Scott et al., 2007; Strike & Posner, 1982). This can be regarded as a fundamental goal of science education and is, thus, recorded in Table 1, which juxtaposes the most essential aspects drawn from the theory review to inform the design of an innovative format for self-learning.

Learning a concept involves adding to existing cognitive structures and qualifies as “meaningful learning” as opposed to routine-facilitating rote-learning (Ausubel, 1969). When introducing a new concept, some fundamental rules that cluster around the idea of crucial features of a concept should be obeyed (*e.g.*, K. Johnson & Bulla, 2021; Kean, 1982; Layng, 2019; Tennyson & Park, 1980):

- Each concept is characterized by a set of critical features that pertain to each of its cases (*e.g.*, metals are oxidized rather than reduced, metals show metallic shine, metals are good electrical and thermal conductors)—sometimes one concept may embrace several sets of critical features as, for example, in coexisting acid-base-concepts (Kean, 1982).
- Several cases of the same concept may be differentiated from each other by sets of variable features (*e.g.*, noble metals are harder to oxidize, base metals react readily with water to form lye, thermal and electrical conductivity are functions of crystalline structure).
- Several examples of the concept must be introduced that exhibit the critical features (*e.g.*, gold as a noble metal, sodium as a base metal, aluminum *vs.* copper regarding conductivity).
- Non-examples violating the concept features must be provided (*e.g.*, oxygen as an electric and thermal insulator, sulfur that does not have a shine, reduction reactions with chlorine).

However, concept-learning need not restrict itself to introducing new concepts but can also extend existing ones (Scott et al., 1992). This is especially important in science where concepts do not exist in isolation but interact and co-define each other (Kintsch, 1988) or combine to form principles (Gagné, 1965). Also, entities that are colloquially referred to as concepts are, in fact, formed by related sets of concepts (Herron et al., 1977): the metals example above draws concurrently on numerous individual concepts (*e.g.*, oxidation, conductivity). This sublime complexity of concepts is characteristic of science and therefore relevant for science education, not least when addressing preconceptions (Asterhan & Resnick, 2020). The viability of the above sketched method of introducing a new (and simple) concept is, thus, put into question. There appears to be no valid description of how complex concepts develop (Rusanen & Pöyhönen, 2013) as well as there appears to be no viable cognitive model to capture conceptual change processes (Clement, 2013).

Science teachers have traditionally relied on one crucial means to support students' concept-learning: textbooks (Bergqvist & Chang Rundgren, 2017; Martin et al., 2012; Thompson et al. 2023). At the same time, it appears to be increasingly problematic for student learning to rely on science textbooks (C. E. Johnson & Boon, 2023; Kahveci, 2010). Standard science textbooks are most often not written for those students with little prior knowledge, as they often exhibit a linguistic complexity and factual density that defies study by naïve readers (Mikkilä-Erdmann, 2002). And even teachers appear to be skeptical of them, considering that the most reported use of textbooks is for teachers' preparation but not for student learning (*e.g.*, Thompson et al., 2023).

Learning from Text

Much of student learning is mediated through written text, from which students are required to (re-)construct conceptual knowledge. Several formats of text have been introduced for this purpose, each having advantages and disadvantages. The following section discusses three formats for text-based learning opportunities: expository text, refutation text, and worked examples.

Expository text in textbooks

Texts that are meant to convey information rather than to entertain are called "expository text", a classic example of which is the textbook (Mar et al., 2021). The textbook is a traditional student resource for learning, which students consider to be reliable and accurate (Thompson et al., 2023)—even if they are known to rarely use textbooks spontaneously (Guzzetti et al., 1997). Several studies have investigated science textbooks with regard to linguistic features; they consistently find that texts in science textbooks tend to be too difficult for the addressed readership due to complicated syntax and inflated vocabulary (Guzzetti et al., 1997; Pyburn & Pazicni, 2014). The suitable age that conventional text readability indices estimate for a given science textbook appears to be one to two years above students biological ages (Calhoun & Rubba, 1993; Puspaningtyas et al., 2020; Soyibo, 1996). Although some unavoidable, linguistic peculiarities of science language (*e.g.,* passive voice and an increased frequency of compound nouns) are responsible for inflated estimation of the conventional readability indices (Calhoun & Rubba, 1993), one must not dismiss the issue easily. Some researchers attribute the rise of learning difficulties in a departure from more narrative-oriented texts when starting science education at the secondary level (Fang, 2006), while narrative texts seem to benefit concept-learning at the primary level (Guzzetti et al., 1993). Note that readability studies—which analyze a given text only structurally—have more recently given way to "comprehensibility" studies (Meyer & Pietzner, 2022; Vojíř & Rusek, 2019) that investigate how students interact with a given text. Students' interactions can be supported (*e.g.*, Leopold & Leutner, 2012) so that a structural, linguistic criterion such as readability need not be an insurmountable obstacle. Comprehensibility support can take two forms—top-down (readers infer sense) or bottom-up (text guides sensemaking; Meyer & Pietzner, 2022)—suggesting that the actual text—notwithstanding interactions with the readers—exerts an influence on comprehension. Therefore, textual complexity continues to be a bottleneck that needs to be taken into consideration when learning in science (Safari et al., 2017). When science texts become incomprehensible to students, they lose their most crucial function. Unsurprisingly, there is research that shows that teachers are skeptical of the potential a textbook has for student learning (Beerenwinkel & Gräsel, 2005; Thompson et al., 2023). Students, when asked, express a wish for texts to be comprehensible, interesting, and rich in examples (Knecht & Najvarová, 2010). Authors suggest that interest could be furthered "by an attractive style of writing that motivates students toward further reading and deeper thought" (Knecht & Najvarová, 2010, p. 10). Having said this, there is also conflicting evidence that students do not prefer narrative texts (Guzzetti et al., 1993; Guzzetti et al., 1997), or that they even prefer expository actualizations of a conceptual change text format—refutation text (see below)—over its *narrative* variation (Hynd, 2001).

Common science texts tend to be heavy on technical terminology, thereby creating a density of information that makes it harder for students to realize where their preconceptions are no longer adequate and how they could align better with a scientific concept (van Loon et al., 2015). Science textbooks have been criticized for introducing more technical terms in a single reading than foreign language teaching would suggest in its domain (Groves, 1995), or for being less readable than textbooks for English as a Second Language for the same age group (Hu et al., 2021). While this situation has ameliorated to some degree, it still was shown to be, on the whole, valid twenty years later (Groves, 2016). Moreover, the introduction of new terms rarely supports a systematic construction of concepts (Härtig, 2014). This all contradicts a tacitly held, valid demand that science textbooks should be suited for student learning (Lodge, 2021), for example, when trying to catch up. Mikkilä-Erdmann (2002) advocates for science texts to actively support concept-building instead of collecting facts; she favors metaconceptual text that gives "direct comment on how to understand a phenomenon" (p. 343). Essentially, this calls for a different structuring of science texts that is better aligned with students' needs when attempting conceptual change in learning.

Table 1 collects Lessons Learned from different branches of science education research to inform an innovative format for supporting student learning. Summarizing from the above, essential design suggestions for expository texts in textbooks are: (1) reduce syntactic complexity, (2) use fewer technical terms, (3) use technical terms to develop a concept, (4) employ narrative text for motivational reasons.

Refutation text

An alternative to expository text from traditional textbooks for supporting students in developing their preconceptions into scientific concepts is conceptual change text. One such format is refutation text that differs from standard expository science text insofar as it explicitly addresses specific preconceptions and then corrects them (*e.g.*, Atasoy et al., 2009; Guzzetti et al., 1997). Relating explicitly to the preconcept can take on different guises: it may be realized in a direct contrast, *i.e.*, by explicitly stating the preconcept and its inadequacy, or through creating discrepant events, *i.e.*, through promoting dissonance by experiencing a contradictory phenomenon and introducing a controversial question (Clement, 2013). Refutation text may start from scratch by creating a cognitive conflict or by extending pre-existing ideas (Scott et al., 1992). These texts are especially valuable for students with little prior knowledge (Ariasi, 2012; Diakidoy et al., 2011; Diakidoy et al., 2016).

It is assumed that learning from refutation texts supports concept-learning by attending to some cognitive principles that subconsciously frame concept-building and cannot be avoided, so one should aim to make use of them (Kendeou et al., 2014):

(1) encoding principle: Once information has been stored in long-term memory, it cannot be undone and might resurface at any time.
(2) passive activation principle: Stimuli in working memory may unconsciously draw up formerly encoded information that can interfere.
(3) coactivation principle: Previously encoded information (preconcept) and updated information need to be juxtaposed, *i.e.*, they need to be present at the same time in working memory if the one is supposed to 'overwrite' the other.
(4) integration principle: Preconceptual information needs to construct a coherent whole together with 'new' information.
(5) competing activation principle: As a consequence of the encoding principle, new stimuli in working memory are prone to activate both the incorrect and correct information, at the same time.

The crucial principles to exploit in teaching appear to be the coactivation-principle—by ensuring that a preconcept is triggered at the same time when the scientific concept is introduced—and the integration-principle—by explicitly advising students how to construct a better aligned concept from both the present concepts. Standard expository text does not usually call out specific preconceptions and therefore cannot live up well to the challenge of conceptual change.

Apart from making use of the above principles, another reason for refutation texts' efficiency could lie in extended time-on-task compared to cursory reading of expository texts, as evidence from eye-tracking studies suggests (Ariasi, 2012).

Conceptual change learning from refutation texts benefits from providing curricular coherence and from introducing meaningful and engaging contexts, which allow students to link their own ideas and experiences (Krajcik & Shin, 2023). More added value lies in integrating analogies and graphics into refutation text (Danielson et al., 2016). Furthermore, the coactivation and integration processes may benefit from encouraging students to reflect on their learning process (Krajcik & Shin, 2023), and from requiring elaborated explanations (Danielson et al., 2016; Kendeou et al., 2014). Where possible, the implementation of analogies promises to support conceptual change as analogies rely on everyday knowledge and can therefore coactivate complex preconcepts in students (Clement, 2013).

Students prefer learning from refutation text while hardly ever resorting to expository text from schoolbooks (Guzzetti et al., 1997; see also Sinatra & Broughton, 2011). The effects from learning with refutation text are typically of medium size and tend to be most pronounced for learning in science education (Schroeder & Kucera, 2022). Using refutation instead of expository text in classes shows improved learning of the targeted concepts (Diakidoy et al., 2003). Changing text flow towards a narrative style does not improve learning from refutation text (Guzzetti et al., 1993), nor does it increase students' acceptance of the texts (Guzzetti et al., 1997).

Again, the most essential design implications from this line of research are to be banked in Table 1: (1) raise awareness of preconcepts, (2) juxtapose and integrate preconcepts with scientifically more adequate concepts, (3) employ contexts that are engaging and well-aligned with the curriculum, (4) introduce analogies as preconcepts, (5) encourage students to elaborate on their concept-building.

Worked examples

One antipode to concept-learning in science education is algorithmic problem-solving. Algorithmic problem-solving can be either considered to belong to lower-order cognitive skills (LOCS, *i.e.*, recalling, comprehending, applying in Bloom's (1956) terms)—as opposed to higher-order cognitive skills (HOCS, *i.e.*, analyzing, synthesizing, evaluating)—, or to be even on a level below LOCS (Zoller, 2002). Student performance in algorithmic problem-solving is lower than performance on LOCS tasks, on which students, in turn, perform lower than in HOCS tasks, which are sometimes referred to as conceptual tasks (*e.g.*, Bius, 2016; Surif et al., 2014; Zoller, 2002). Therefore, neglecting concept-learning and overemphasizing algorithmic problem-solving should be discouraged ("algorithmic calisthenics"), as this does not support students' conceptual understanding (Nakleh & Mitchell, 1993). Duschl (2008) likewise points out that conceptual and epistemic (*i.e.*, problem-solving) learning need to form a symbiosis. Therefore, innovative formats of learning conceptual knowledge need to be explored. It might be worthwhile to explore some of the techniques employed in problem-solving learning and to adapt these to conceptual learning, such as learning from worked examples.

Problem-solving is an approach to teaching that aims at equipping students with flexible strategies and methods to apply to a diversity of analogous problems (*e.g.*, Chen et al., 2023). Its basic tenet is that a powerful problem-solution strategy can be abstracted from the situation in which it was acquired and can be generalized to apply in new, similar problem situations. Research on transfer from learning with worked examples is unfavorable regarding far-transfer effects (Moreno, 2006).

Concrete examples support learners when interpreting general explanations, while at the same time they depend on general explanations to classify examples (Reimann, 1997). During initial skill acquisition, learners improve their understanding better by studying worked examples—this is known as the worked example principle (Renkl, 2005, 2014b, 2021; Sweller & Cooper, 1985). Worked examples consist of a problem statement, a problem solution which is provided in a step-by-step manner, and the solution to the problem (Hilbert et al., 2008; Renkl, 2021). Hence, worked examples present a complete problem-solving cycle, in which students are frequently encouraged to anticipate solution steps (Stark, 1999) and which provide explanations for solution steps (for an overview see Renkl, 2014b, 2021).

Traditionally, worked examples are used in algorithm-based areas of mathematics (*e.g.*, Gerjets et al., 2006; Leppink et al., 2014), physics (*e.g.*, Kalyuga et al., 2001), or statistics (*e.g.*, Paas, 1992). After introducing a theorem, law, or general principle, worked examples demonstrate how to use this knowledge before learners start working on more open problem-solving tasks (Reiss & Renkl, 2002; Renkl, 2005, 2014b, 2021; Renkl et al., 2009).

Novice learners especially prefer worked examples as they enable them to quickly solve analogous problems on their own (Atkinson et al., 2000). When learners are provided with an instruction *and* an example, they mainly rely on the examples even if the instruction is declared to be important (LeFevre & Dixon, 1986). Learners who study worked examples make fewer mistakes and need less time because they do not process irrelevant operations during performance compared to learners who work on problem-solving tasks during skill acquisition (Sweller & Cooper, 1985). A longitudinal study showed that students who studied worked examples instead of attending a regular math class needed less time to study and performed comparable to or better than the control group (Xinming Zhu & Simon, 1987). Even when worked examples are provided for studying at home, students from a worked example group outperformed students from a problem-solving group on subsequent performance tests (Ward & Sweller, 1990).

However, some major limitations for the worked example principle are: (1) that worked examples need to be carefully designed according to design guidelines to be effective (*e.g.*, Renkl, 2014a, 2014b, 2021), (2) that worked examples are primarily beneficial to novice learners as skilled learners might get distracted by a scaffold that they do not need ("expertise reversal principle" see Kalyuga, 2014, 2021), (3) that learners need to actively process worked examples (Renkl, 2014b, 2021; Renkl et al., 1998; "self-explanation principle" see Chi, 2021), and (4) that worked examples should not remain an isolated task format; their strength lies in introducing students to a problem-solving approach but not in advising transfer to novel, more dissimilar problems (*e.g.*, Renkl & Atkinson, 2012; Jalani & Sern, 2015). For this, supplementary measures such as self-explanation are suggested (*e.g.*, Fiorella, 2023) or a combination with problem-solving tasks (*e.g.*, Renkl, 2021; van Gog et al., 2011).
Even though the worked example principle originally was investigated in algorithmic domains it has also been shown to be valid in non-algorithmic domains, introducing heuristic task solution (Hilbert et al., 2008; Renkl, 2005). Worked example research is much intertwined with research in Cognitive Load Theory, as worked examples aim at optimizing cognitive load during learning (*e.g.*, Renkl & Atkinson, 2012; Sweller & Cooper, 1985; Ward & Sweller, 1990). Therefore, worked example design has been strongly influenced by research on the Cognitive Theory of Multimedia Learning (*e.g.*, Mayer & Fiorella, 2021) that suggests general design principles and guidelines (Mayer, 2020) for optimizing cognitive processing when learning from materials that include more than one source of information, *e.g.*, text and images.

Regarding students learning heuristic and algorithmic content, research suggests these Lessons Learned to be recorded in Table 1: (1) provide a stepwise development of the learning aim, (2) respect Design Principles and Guidelines of the Cognitive Theory of Multimedia Learning, (3) encourage students to self-explain the presented information.

Lessons learned for concept-learning

Students are expected to acquire new conceptual knowledge through learning in schools. They can be supported in this endeavor by instructional texts. Traditional expository texts are frequently too difficult to support student understanding. Conceptual change texts, such as refutation texts, are advocated for improving students' alignment of preconcepts with scientifically more adequate ones. These texts raise students' awareness of preconcepts before introducing and integrating updated concepts.

Furthermore, refutation texts benefit from the introduction of analogies, graphical representations, and self-explanation tasks for students. The very same design strategies are effective in learning with worked examples—that traditionally deal with algorithmic or heuristic learning—to support problem-solving abilities. Worked examples provide smaller steps at the beginning and make strategies explicit until students have gained sufficient expertise to take bigger steps on their own. They support students by requiring them to elaborate on their freshly acquired knowledge, thereby allowing contrasting new knowledge with old ideas.

The above is a comprehensive summary (Lessons Learned) of the more detailed discussions of the theoretical background. Each of the reviewed branches of science education research necessarily brings its own focus to investigating the effectiveness of learning. Assuming that learning is complex and multifactorial in its conditions, novel formats of study should consider as much research evidence as possible. Therefore, essential aspects of the above research are comprehensively considered when designing an innovative format for student self-study. Regarding concept-learning, this review suggests to (see Tab. 1): (1) develop scientifically adequate concepts stepwise, (2) start learning from students' preconcepts, (3) address preconcepts explicitly where there are misconceptions, (4) use narrative language for motivation and reading ease, (5) require students to concurrently monitor their concept-building by reflection and self-explanation prompts, (6) introduce technical terminology functionally, *i.e.*, to build or to close a concept. Merging evidence from research on learning effectiveness, thus, is expected to inform the design of incremental, student-paced learning opportunities for concept-building. The resulting concept-building worked examples are an innovative format for self-study that decidedly emphasizes an undernourished pillar of scientific literacy: having a knowledge of scientific concepts.

Table 1

Combining insights from different strands of science education research to inform the design of an innovative format for science concept-learning

Challenges of concept-learning	Lessons Learned from research on learning with			Consequences for supporting concept-learning
	expository texts in textbooks	refutation texts	worked examples	
Aligning preconcepts with scientifically more adequate concepts	Support reading comprehension by • Reducing syntactic complexity • Using fewer technical terms • Using technical terms to develop a concept • Employing narrative text for motivational reasons	Support concept-building by • Raising awareness of preconcepts • Juxtaposing and integrating preconcepts with scientifically more adequate concepts • Employing contexts that are engaging and well-aligned with the curriculum • Introducing analogies as ‘preconcepts’ • Encouraging students to elaborate on their concept-building	Support student learning by • Providing a stepwise development of the learning aim • Respecting Design Principles and Guidelines of the Multi-media Theory of Learning • Encouraging students to self-explain presented information	Design learning tasks that • Develop scientifically adequate concepts stepwise • Start in students’ preconcepts • Address preconcepts explicitly where there are misconceptions • Use narrative language for motivation and reading ease • Require students to concurrently monitor their concept-building by reflection and self-explanation prompts • Introduce technical terminology functionally, *i.e.*, to build or to close a concept

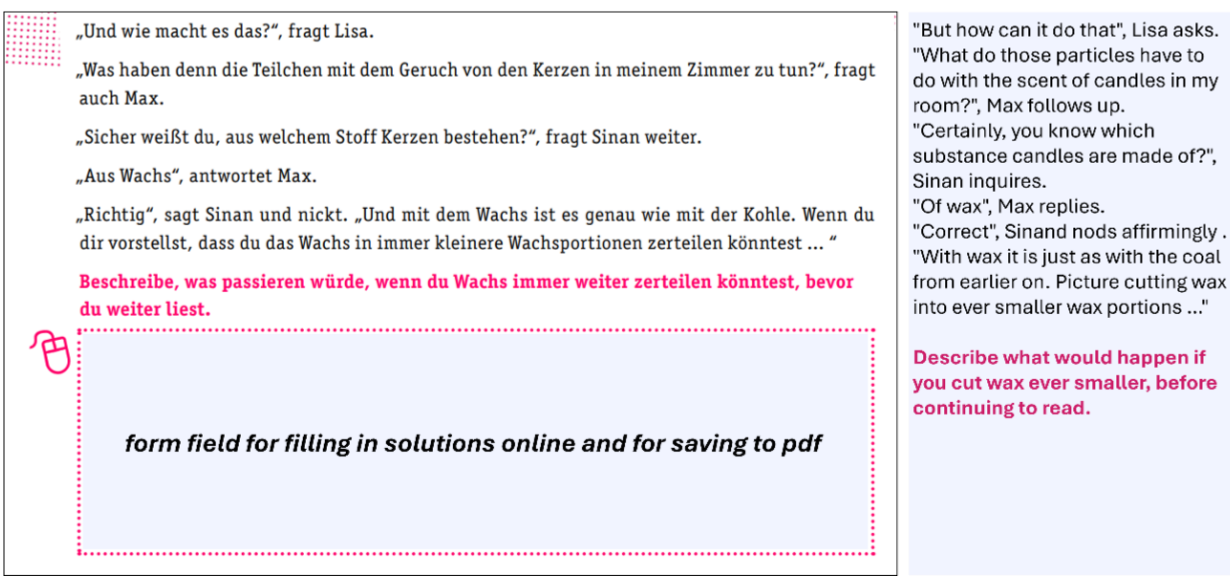
Concept-building worked examples – A development project

The proposed concept-building worked examples stem from a development project funded by the Müller-Reitz Foundation. Its aim was to develop learning materials on basic concepts from secondary chemistry education in Germany (Schüßler et al., 2016). The complete learning materials are written in German and were explicitly meant for phases of self-study (*e.g.*, to catch up after an absence due to illness or for remedial purposes). We did not design the materials as primarily in-class teaching materials or for homework. In a word: We designed the concept-building worked examples as a substitute when no teacher is available, and the textbook does not help.

We planned for a publication and distribution free of charge so that use of self-study materials would not be hindered by economic status. This—and later the sheer extent of developed materials (Tab. 2)—prohibited a print-version, and we decided to arrange the concept-building worked examples in a ubiquitous file-format distributable easily via the internet. We designed the concept-building worked examples so that they could viably be displayed as pdf-files. We actualized some interactive elements (*e.g.*, requiring students to provide written answers) by means of form fields (Fig. 1).

Figure 1

Example slide "form fields" (blue tinted boxes: translation and comment for screenshot from Scientific Models-Diffusion (10/63))



Aiming at access from different portable end devices we organized worked examples in small screens so that scrolling could be kept to a minimum. Therefore, composition of the concept-building worked examples made use of presentation software slides, that also required authors to keep it short and simple. The design of the concept-building worked examples drew on research literature referenced in the theoretical background. The following section will illustrate how worked example research informed the design of the concept-building worked examples.

Cumulative concept-building through sets of worked examples

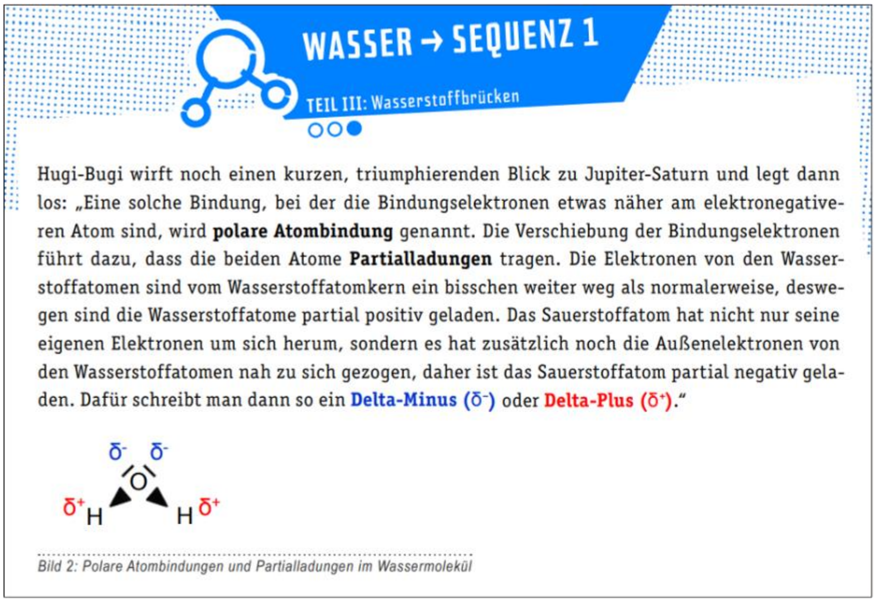
Instead of presenting an algorithmic or a heuristic solution to a problem, the proposed worked examples serve to develop conceptual knowledge in chemistry by introducing conceptual knowledge necessary to explain a scientific phenomenon. The innovative format of concept-building worked examples strives to combine beneficial features of worked examples with what is known about learning from texts. Concept-building, thus, can be well supported, ultimately relying on the above principles to introduce a concept. These principles are realized in all the concept-building worked examples without forcing them into a rigid pattern. Rather, the narrative flow and context determine how and when they are introduced:

- providing defining features of a concept with examples (*e.g.*, acid molecules contain a polarized covalent bond to at least one hydrogen atom that can dissociate from the molecule; acids turn universal indicator red)
- providing non-examples that do not share defining features (*e.g.*, hydrogen atoms not connected by a polarized bond cause no acid reaction)
- applying the concept to other examples (*e.g.*, translating the dissociation of protons from phosphoric to citric acid)
- differentiating between examples and non-examples in a dialogue between novices and experts (*e.g.*, "Wow, that's a lot of H-atoms in citric acid." – "And even more other atoms." – "Yes, but only a few of the H-atoms are connected through a polarized bond.")
- enriching the concept with related concepts (*e.g.*, introducing pH as a measure of proton concentration; modelling neutralization as a process to capture dissociated protons)
- extending the concept (*e.g.*, introducing bases as substances that bond dissociated protons; bases turn universal indicator greenish-blue)

Concept-building worked examples were divided into sets of smaller, self-contained examples (see Tab. 2). This structure accounts for the inherent complexity of scientific concepts that frequently combine several concepts into an overarching one. Above this, the division into smaller, self-contained worked examples allows students to plan breaks when studying (Renkl, 2014a, 2014b, 2021). Presenting them with a complete set of slides for an overarching concept could probably be detrimental motivation-wise. Starting with the second example in a set, students are reminded of central ideas from the previous example(s). When studying the examples students are asked to answer questions, to give their ideas on a topic, or to apply their freshly acquired concept knowledge. They enter their replies into form fields of the pdf files enabling saving solutions—this is meant to encourage self-explanation (Fig. 2). Individual examples close with a self-assessment in which students are encouraged to write down their understanding of central ideas from the concept; again, form fields are provided. Example solutions allow for self-assessment.

Figure 2

Example slide "recapitulation" (Water – hydrogen bonds (6/45))



Hugi-Bugi casts a short, triumphant glance over at Jupiter-Saturn and rambles on: "Such a bond, in which the binding electrons are somewhat closer to the atom with the higher electronegativity, is called a **polarized atom bond**. The shift of binding electrons causes both the atoms to carry **partial charges**. Hydrogen's electrons are a little bit further away than usual from hydrogen's nucleus and so the hydrogen atom is charged partially positive. Thus, the oxygen atom doesn't just have its own electrons around. It even attracts the hydrogen's electrons so that it becomes charged partially negative. We note this with **delta minus (δ-)**, **delta plus (δ+)** respectively."

[*image 2: polarized atom bond and partial charges in a water molecule*]

The individual worked examples are divided into meaningful sections, each of which is presented on a single slide ("segmenting principle" see Mayer, 2020; "meaningful-building-blocks guideline" see Catrambone, 1998; Gerjets et al., 2006; Renkl, 2014a, 2014b, 2021). Individual slides typically contain a complete solution step/idea for building the concept—rarely is an idea spread over more than one slide, so that a slide could principally stand on its own, which necessarily leads to some slides that are lean in textual information. This structural scaffold invites learners to take the time they need to adequately process information of the just-read paragraph before reading the next paragraph (pausing and temporal cueing: Mayer & Pilegard, 2014; Spanjers et al., 2012).

Table 2

Overview of covered concepts and topics in concept-building worked-out examples (Schüßler et al., 2016), plus length (slide count)

Concept (set of examples)	Topic (individual example)	Slides (#)
naming of alkanes	straight-chained alkanes	39
	simple-branched alkanes	48
	multiple-branched alkanes (mono-substituting side chains)	46
	multiple-branched alkanes (poly-substituting side chains)	40
atomic models	Rutherford's model	50
	protons and neutrons	42
	isotopes	42
	Bohr's model	52
water	geometry of the water molecule	71
	surface tension	41
	hydrogen-bonds	50
science models	diffusion	67
	changes of state of matter	79
	elements, atoms, molecules	56
	example of a chemical reaction: incomplete combustion	49
	complete combustion	66
redox reactions	oxidation reactions with oxygen	36
	redox reaction of iron oxide	34
	redox reaction of silver sulfide	54
acids (coke)	acid solutions	44
	pH	38
	neutralization	43
acids (red tea)	acid solutions	40
	pH	36
	neutralization	45
acids (wine gum)	acid solutions	62
	pH	41
	neutralization	37
chemical substances	properties	44
	mixtures	41
	separation methods	64
	extraction	22
	introduction to the chemical reaction	36
9 concepts	34 worked examples	1554

Note: "acids" was developed in three different contexts for the sake of an evaluation study of these self-study-materials (Schüßler, 2017). The concepts introduced in the worked example sets are shared between the contexts.

Relating to the students' perspective in worked examples

A central issue to be addressed in the innovative task for concept-learning was to emancipate students from their textbooks' motivational pitfalls. Students want to read texts—if they must—that exhibit "an attractive style of writing that motivates students toward further reading and deeper thought," which can be achieved by making texts comprehensible, interesting, and rich in examples (Knecht & Najvarová, 2010, p. 11). Text comprehension—as estimated by reading indices—can be improved by employing a narrative style of language that is less heavy on passive constructions, impersonal subjects, or hypotaxis (Safari et al., 2017). Bearing in mind that the proposed tasks are meant for students who cannot easily learn during classes or from textbooks, it is assumed that the motivational windfall gained from narrative embedding may lead to the generation of situational interest, which in turn can exert a beneficial effect on learning (Hulleman et al., 2010; Xihe Zhu et al., 2009). Therefore, introducing cover stories with fictional characters for worked examples might allow exploitation of these motivational advantages (see also Avraamidou & Osborne, 2009).

A variation of contexts has been shown to exert an influence on students' situational interest, favoring everyday-related and uncommon contexts (Habig et al., 2018). Therefore, a variety of contexts was covered through which students encounter the chemical concepts: *e.g.*, teenage boys wondering at the pool why there is phosphoric acid in coke, pre-schoolers learning about mixtures and reactions when baking muffins with their babysitter, a pair of siblings being introduced to oxidation and reduction by their grandfather who is sorting through rusted screws, or a bunch of extra-terrestrial schoolkids learning about earth and that special (*i.e.*, anomalous) substance water.
These cover stories allow exploiting the potential of what van Gog and Rummel (2010) term "coping models" and "mastery models" by introducing fictional characters with different levels of expertise. Coping characters are typically novices who try to succeed in something (cope); they can serve as figures of identification or role models; they are the stand-ins to commit typical mistakes and to ask dumb or naïve questions (Fig. 3). Mastery characters on the other hand are more progressed in the matter in question and are understood to be experts in the story; they present relevant knowledge correctly, answer questions competently and correct typical mistakes (van Gog & Rummel, 2010). Thus, worked examples can use cover stories with mastery and coping characters to develop a concept step-by-step by first discovering a problem, then discussing it with each other, and finally arriving at a joint solution. Koenen (2014) used such cover stories in worked examples to foster inquiry learning. Likewise, Kölbach's (2011) worked examples resorted to cover stories to demonstrate how conceptual knowledge from chemistry could be applied to explain phenomena.

Figure 3

Example slide "naive question" (Science models - Elements, atoms, and molecules (13/51)

"If we heated wax in a cup till it boiled – in a pot on the stove, for instance –, there would indeed curl up gaseous wax above the cup.
However, when we light a candle, no gaseous wax curls up above it", Sinan tells them.

[image 4: burning candle]

"But where's the difference in that", Max interrupts.

"The difference is, that wax which is heated in a pot *boils*, while wax in a burning candle *combusts*", Sinan says.

Coping characters serve as figures of identification as they have about the same age as the potential learners; they can be modelled on the intended readership regarding sex and ethnical background, thus extending the potential for self-identification and for providing positive role models ("model-observer similarity principle" see Renkl, 2014a). They do not have—from the start—the necessary conceptual knowledge to explain the phenomenon they have discovered. By making assumptions, asking questions, and discussing their ideas with each other, they provide positive role models for an active involvement with the phenomenon and the relevant conceptual knowledge (Fig. 4). They serve as projections of the learners' assumed preconcepts without necessitating the learners themselves to disclose their insufficient knowledge.

Figure 4

Example slide "dialogue" including preconception (Redox reactions – Oxidation reactions with oxygen (28/32))

"But, oxygen is a gas!", Lennart protests. „It doesn't weigh anything."
"Each atom has its specific mass", his grandfather corrects, "Even atoms of gaseous substances. Therefore, the screw's mass increases when more iron oxide forms."
"And you can really weigh this?", Lia inquires fascinatedly while picturing herself putting the screws onto grandma's ancient scales.
As if having guessed at her thoughts, grandfather replies: "Grandma's ancient scales certainly could not do this – the difference is far too minute. But very fine scales could work."
"However", he continues, "we would need to prevent parts of the iron oxide from crumbling off when touching the screws."
Lia is somewhat disappointed and murmurs, "Pity."

Making preconceptions explicit can prevent learners from making the same mistakes (D'Mello et al., 2014; Große & Renkl, 2004, 2007; "studying errors guideline" see Renkl, 2014a., 2014b, 2021; Roy & Chi, 2005) or correct already existing preconceptions. Coping characters can, therefore, support conceptual change, as their introduction allows students to co-activate relevant preconceptions and integrate them with the intended scientifically adequate conception (Kendeou et al., 2014). Thus, they turn into identification figures as well as learning facilitators that can inquire "about everything you always wanted to know but were afraid to ask".

Hartman et al. (2020) showed that observing someone engaging in problem-solving can support students as they become aware of their own knowledge gaps. At the same time, coping characters can inspire learners to behave in a similar way and attempt to formulate elaborations, which might to some extent compensate for poor self-explanations (Stark, 1999). Even self-explanations that attend to incorrect information contribute to concept-building: Siegler (2009) showed that students who explained both the correct and erroneous problem solutions of two children outperformed students who explained only the correct solution of another person.

Accordingly, the introduction of a mastery character has the advantage that instructional explanations can be integrated into the dialogue of a worked example (Nokes et al., 2011; Renkl, 2002). Mastery characters provide scientifically adequate explanations for an encountered phenomenon. That means that instead of presenting a mastery performance—as would be the case in traditional heuristic and algorithmic worked examples—the proposed character presents conceptual mastery information in a Socratic manner. This is considered important for learners with low prior knowledge (Renkl, 2014b, 2021) and for learners who do not self-explain information or solution steps to themselves ("explanation-help guideline" see Renkl, 2014a, 2014b, 2021; Roy & Chi, 2005). Roelle et al. (2017) showed that students need to adequately organize instructional explanations into coherent mental representations in order to profit from studying worked examples. Hence, they conclude that learners should be supported not only by self-explanation prompts but also in organizing instructional explanations.

Design principles implemented at the example level

So far, some overarching design criteria have been introduced that pertained to the content of written text rather than to its graphical presentation. This section will change grain size and zoom in on the layout of worked examples to illustrate how some well-researched design principles from the Cognitive Theory of Multimedia Learning (Mayer, 2020) have informed the design of concept-building worked examples. The presentation necessarily has an exemplary character, and not each principle might feature equally prominently in all the concept-building worked examples.

The worked examples exploit the multimedia principle (Mayer, 2020, which requires learning materials to complement textual with pictorial information by presenting text and figures in proximity ("spatial contiguity principle" see Mayer, 2020), *i.e.*, on the same slide. Where textual and pictorial elements correspond, they are given in the same color (color coding); novel information is printed in bold face, while parts of complex figures, which are not explicitly addressed in the respective textual information, may be faded out (greying out; all techniques responding to "signaling principle" see Mayer, 2020, Fig. 5).

Figure 5

Example slide "spatial contiguity, color coding, signaling, self-explanation" (Redox-reactions oxidation reactions with oxygen (17/32))

„Es gibt nicht nur unser Eisenoxid, sondern noch viele andere Oxide", fährt Lias und Lennarts Opa fort.

„Zum Beispiel **Kohlenstoffdi-*oxid***?", ruft Lia aufgeregt. Den Begriff hat sie letzte Woche im Biologieunterricht gelernt, als es um die Atmung ging. Die Luft, die Menschen ausatmen, enthält mehr Kohlenstoffdioxid als die Luft, die sie zuvor eingeatmet haben.

Ihr Opa nickt wieder zustimmend. „Richtig. Kohlenstoffdioxidmoleküle entstehen, wenn **Kohlenstoffatome** mit **Sauerstoffatomen** reagieren."

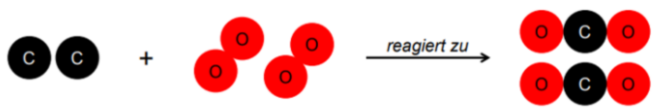


Bild 3: Oxidation von Kohlenstoff

„Und das ist dann auch so eine Oxidation?", fragt Lennart noch mal nach.

Sein Opa nickt erneut.

Fasse zusammen, was eine Oxidation kennzeichnet und was ein Oxid ist, bevor du weiter liest.

"There isn't only our iron oxide but many more oxides", Lia and Lennart's grandfather adds.

"**Carbon di-*oxide***, for instance", exlaims Lia excitedly. She has learned the term in last week's biology lesson when they were talking about respiration. The air exhaled by people contains more carbon dioxide than the air they inhaled before.

Her grandfather nods his head in confirmation, "Correct, molecules of carbon dioxide form when **carbon atoms** react with **oxygen atoms**."

[*image 3: oxidation of carbon*]

"And this also is such a reaction?", Lennart wants to make sure.

His grandfather nods again.

Please, summarise, what defines an oxidation and what an oxide is before continue reading.

Introducing multiple characters into a cover story allows unfolding of the worked example in a dialogue, which helps to better speak to learners ("personalization principle" see Mayer, 2020). Even if the mastery character puts their question to the coping character, the "you" addresses the student reader, too. It helps that questions in the dialogue evolve organically and are, therefore, understood to be necessary as opposed to typical textbook tasks that appear to be disconnected from prior discourse.

Active processing of the worked example by the learner is necessary for successful learning. Self-explanations generate information that goes beyond the text and help to connect new information with each other and with existing concepts in a meaningful way ("self-explanation principle" see Chi, 2021). Since only few learners spontaneously show sufficient self-explanatory behavior (Chi et al., 1989; Renkl et al., 1998), self-explanations should be supported with prompting measures (Stark et al., 2008). These prompts can occur in the form of encouragement or incentives to think something through (Chi, 2021; Roy & Chi, 2005; Wylie & Chi, 2014; see Fig. 5). These incentives do not necessarily require students to give a written answer but should activate students cognitively. Students might be prompted to answer a question, summarize for themselves what they have learned so far, identify crucial information in one of the characters' utterances, or enter into a thought experiment. They must start an inner dialogue about what they have learned. In this way, new information is derived from the explicitly given information. Comparisons with the mental model reveal differences and initiate concept changes (Chi, 2000). If not taken up actively, received information cannot be used for concept-building; this would be akin to waiting for the flood to heap up a sandcastle.

Design guidelines implemented at the example-set level

Worked examples should not be administered as one-shot interventions but function most effectively when forming a set of examples. Segmenting an overarching concept thus allows for the composition of shorter and, therefore, better to digest entities of study. At the same time, it enables introduction of repetition and recall when spreading study for concept-building over some time (also "self-explanation").

Providing more than one worked example on a topic proves beneficial for learning from worked examples. Only by encountering several worked examples can learners distinguish shared structural features—*i.e.*, critical features of a concept—from irrelevant surface features ("example-set guideline" see Renkl, 2014a, 2014b, 2021; also Atkinson et al., 2003). In addition, when presenting a series of worked examples, omission of individual solution steps that have been introduced in a prior example encourages learners to fill these steps themselves. It is suggested to start at the worked examples' end with the omissions so that the familiarized structure of the worked example can serve as a scaffold leading up to the omission ("fading guideline" see Renkl, 2014a, 2014b, 2021; also Atkinson et al., 2003). When designing the worked examples, we tried to take all these design principles into account as much as possible to develop learning materials that help and motivate learners to acquire chemical conceptual knowledge independently.

Discussion

This article introduces an innovative format of learning text: the concept-building worked example. It has been developed from merging research on two crucial aspects of learning: concept-learning and learning from texts. Its basic premises can be outlined thus: Scientific concepts are complex constructs that take time to be constructed; understanding can result neither from hearing them spoken once or twice in classrooms, nor from condensed textbook representations. "Understanding" here refers to a complex process of "selecting key information from the provided learning material, organizing it into a coherent structure in working memory, and integrating it with existing knowledge from long-term memory" (Fiorella, 2023, p. 53). Just like in the case of complex algorithms and heuristics, science concepts can be developed stepwise keeping pace with students' constructive learning by means of worked examples.

The worked examples in this paper have been evaluated empirically (Schüßler, 2017)—the scope of the article prohibits a comprehensive introduction to the study, so that a brief outline of results may suffice: Student learning (N=436, M_{age}=14.1, 49.8% female) benefits from working with these worked examples with large effect sizes (d = 0.88). The learning gains can still be detected in a follow-up test, albeit to a lesser extent (η^2_p = .333). Students show decreasing mental effort and self-reported perceived task difficulty over the course of working through a set of worked examples, which is suggestive of successful cumulative construction of concepts.

Given that the concept-building worked examples' basic rationale—allow time to construct a concept—should pertain to all learners, their implementation could benefit minoritized or otherwise disadvantaged students, too. Jones & Burrell (2022) claim that there is a subtle shift in the quality of instruction when looking at teaching minoritized students. Some of this might be traced back to socialized prejudices, some to unequal access to high-quality learning opportunities. Self-study materials might be a remedy in this situation as they are insensitive toward their users' personalities (at least regarding feedback). Rolling out worked examples online, free of charge, provides unhindered access to science education materials to a substantial number of students. Organizing science education content in smaller, digestible entities—*i.e.*, sets of self-contained worked examples— is a form of "Microlearning" that supports learners to focus and to learn at their own pace (Mostrady et al., 2025).

Moreover, offering the materials online, allows today—more than at the time of their original development—an easy combination with other tools. Students who are visually challenged can have the example read out to them by assistive technology, moving toward equitable science education (Jones & Burrell, 2022). Automated translations into a multitude of languages using AI-translation engines are virtually only one click away. Even if these translations turned out to be less than perfect, they should still form a sound basis from which to do the fine-tuning of a text. This could ease production of learning materials substantially as opposed to starting from scratch—especially for practicing teachers who are chronically short of time. Having based the materials on recent international, *i.e.*, not culture-specific research on learning and science education suggests that the underlying mechanisms are transferable. There is no reason to assume that the concept-building worked example should work less effectively in a sub-Saharan or a Western suburban locale. Still, this type of material might speak to some students more than to others; but this is the case for each offer science education makes. This should not prevent dissemination but encourage further development with an innovative focus serving the needs of different clienteles.

Having stressed the advantages and potentials of concept-building worked examples, one must not turn a blind eye to their limitations: Does their exclusive online presence not keep them from those students who lack the technological means to access them (Mostrady et al., 2025)? Are the covered concepts still valid considering shifting philosophies of scientific literacy (*e.g.*, Osborne, 2023)? Given students' growing overreliance on generative AI (*e.g.*, Bauer et al., 2025), would they be as accepting of such a format as students of Schüßler's (2017)? Being drafted from a white Western perspective, how equitable can they really be (Jones & Burrell, 2022)—even if they try to contradict stereotypes by making girls and migrants the heroines and heroes; or need this today be considered cultural appropriation?

Some of these critical issues do not touch on the *fundamental* design principles but on *superficial* authorial decisions that could easily be reversed should one wish to adopt the concept. Some others might need reflection and reassessment of the goals of science education. Others again require us to self-critically reflect which benefits lie in technological innovation and which risks they bear. For example: Which is the most reasonable way to incorporate AI into learning scenarios, and how can we ascertain that students remain critical of AI outputs (*e.g.*, Bauer et al., 2025)?

Conclusion—Looking back and looking forward

This manuscript, not being a traditional research paper or classical review, needs another kind of ending that still provides summary but also opens perspectives.

Science education has gone a long way to learn how it can support students to learn how to do science. Considering that *doing* something needs *knowing* something in the first place, we still have too little knowledge of how we can help students build the complex concepts of science from which their "doing science" can commence. We, as a discipline, are rich in teaching methods, inquiry practices, and explanation videos. Yet, we are still underdeveloped textbook-wise—approaches to embed science into concepts (Bennett & Lubben, 2006; Parchmann et al., 2023) or to emphasize inquiry practices (Bennett et al., 2007) have made significant contributions, but they have not specifically addressed the issue of learning a concept. Worse still, textbook publishers appear to have succumbed to the challenge of producing textbooks that are as thin as possible since young people allegedly do not read. This is foolish for two reasons: If we consider reading to be essential for leading a reasonable and informed adult life, we must not lower the demands on students' reading abilities but raise them (Leisen quoted in Meyer & Pietzner, 2022). Secondly, the same young people who allegedly do not read continue to devour the seven *Harry Potter* novels, which come to over 3'000 pages. Young people do read, but they do not read everything—and least of all, will they read something that does not take them, nor their interests, nor their needs seriously. And there goes the textbook.

By composing texts that young people might deem interesting and entertaining to read, concept-building worked examples invite students to *engage* with instructional text—if a text cannot achieve this, learning will probably not be initiated. The project chose to compose learning texts of considerable length despite a general trend to create text-lean environments—again, if young people read *A Song of Ice and Fire* or the *Lord of the Rings* trilogy, we should not assume that text length is the most crucial criterion for their disinclination towards science texts. If the materials should find adoption (or adaptation) in other locales it would acknowledge the work effort put into developing the innovative format. If, above this, the format should be convincing for other researchers to adopt to different subjects and concepts, the acknowledgment would be taken to a wholly different level. In any case, we are convinced that science education must not forget to find ways of supporting students to get acquainted with scientific fact—googling something or reproducing AI outputs cannot substitute for *bona fide* scientific literacy. "Doing science" can only grow from "knowing science"—neglect either of these and scientific literacy is no longer attainable.

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