Chapter 12
Instructional Explanations in Physics Teaching

Christoph Kulgemeyer and David Geelan

Abstract Explaining physics is at the core of physics teaching. Teachers explaining science matter is surely a standard situation in the science classroom. Such verbal attempts with the goal to engender students' understanding have been described as 'instructional explanations'. When planning an instructional explanation as a part of their science teaching teachers might wonder about different questions:

- What is 'explaining', what are 'instructional explanations'—and is that not a form of outdated, teacher-centred instruction?
- What are the characteristics of effective instructional explanations? Can instructional explanations be effective at all or is it always the better choice to motivate students for self-explanations?
- Is there a 'general rule of thumbs' to decide as a teacher what and when to explain?
- How can I plan an effective instructional explanation and how can I integrate it into my teaching?
- There are so many explaining videos on physics topics—can I rely on them? How can I integrate explaining videos into effective science teaching?

The chapter will address all of these questions by referring to a framework of effective instructional explanations based on empirical studies from science education and instructional psychology. The results of these studies will be described in the form of core ideas of effective instructional explanations and their integration into a learning process. We will discuss circumstances under which a physics teacher might rely on instructional explanations—and we will describe when to better avoid them. Finally, we will apply the core ideas on explaining videos (e.g. from YouTube) and discuss how to use them in science teaching (e.g. flipped classroom, students producing their own explaining videos).

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H. E. Fischer and R. Girwidz (eds.), *Physics Education*, Challenges in Physics Education,
https://doi.org/10.1007/978-3-030-87391-2_12

12.1 Introduction

It is a common situation in science teaching: A teacher wants to introduce a new concept in physics such as Newton's third law. Of course, several decisions must be made about how to teach the new concept. These decisions might include the question of whether students should mainly work on their own to *discover* the concept, or whether the teacher will present the content structure. The first option would include a lot of *self-explaining* on the part of the students, whereas the second option would incorporate *instructional explanations* given by the teacher. Instructional explanations, in this case, can be understood as a teacher's verbal talk (combined with an appropriate use of tools like visualizations, representations forms, demonstrations, …) made with the intention of enabling students to develop an understanding and make sense of a concept or principle.

To decide which way to go, a teacher might think about a number of different questions, for example:

1. What is *explaining*? What are *instructional explanations*? Isn't that a form of outdated, teacher-centred instruction?
2. What are some of the criticisms of explaining in science teaching?
3. What are the characteristics of effective instructional explanations? Can instructional explanations be effective at all? Or is it always a better approach to motivate students to develop self-explanations?
4. Is there a *general rule of thumb* to decide as a teacher what and when to explain?
5. How can I plan effective instructional explanations and integrate them into my teaching?
6. There are so many explanation videos on physics topics—can I rely on them? How can I integrate explanation videos into effective science teaching?

These questions and more are dealt with in the following sections in this chapter, based on empirical research in science education and instructional psychology (see Fig. 12.1). It is important to highlight the fact that the focus of this chapter is on

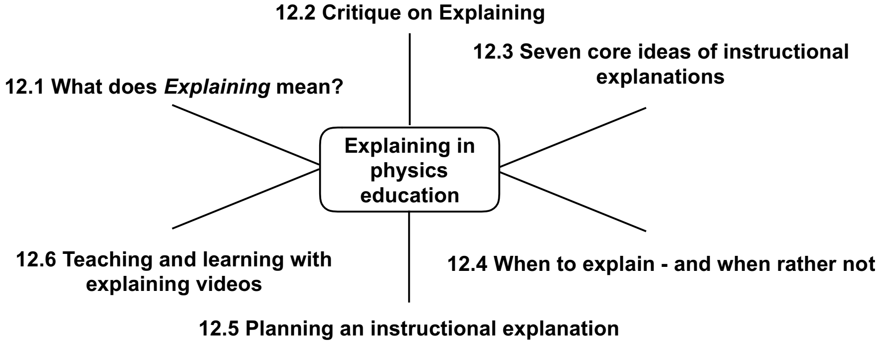


Fig. 12.1 Overview of the chapter

verbal explanations—how textbooks should include written explanations is beyond its scope. There are, however, a number of publications on this topic (e.g. Chambliss 2002; Mamiala 2002; Smolkin et al. 2013; in German: Kulgemeyer and Starauschek 2014).

12.2 What Is Explaining and What Are Instructional Explanations?

To clarify the term *instructional explanation*, we need to define the concept of *explaining*. In this section, we do so by describing differences between and commonalities of three (seemingly) similar concepts:

- Explanation and argumentation
- Scientific explanations and instructional explanations
- The process of explaining and its (temporary) product, the explanation

As mentioned above, an instructional explanation of a concept can be understood as a mainly verbal attempt on the part of a content expert to enable a novice to come to understand and make sense of the concept. Explaining is not limited to verbal language and should by all means be supported by media, representational forms such as diagrams, equations, videos and animations/simulations, experiments and various other features. The intention of the action of *explaining* is the most important part: An instructional explanation has the goal that someone seeks to support someone who attempts to understand a concept. That is the main difference between explanation and argumentation: The latter primarily aims at convincing someone to share or adopt a view or position. On a structural level, argumentation and explanation share many similarities (e.g. Osborne and Patterson 2011) but the goals of each action are fundamentally different.

Instructional explanations are a special kind of explanation and differ from scientific explanations in a number of ways (Geelan 2012). Scientific explanations are the kind given by scientists in formal communications such as in scientific journal articles. They are characterized by specific forms and conventions of communication in science.

For physics, probably the most important form of scientific explanation is the *deductive-nomological* explanation (Hempel and Oppenheim 1948), also known as the *covering-law* model of explanation. Other forms of explanations occur, for example, inductive-statistical explanations, teleological explanations or narrative explanations, but these are of less importance for school physics (with the very important exceptions of quantum and nuclear physics). The core idea of a covering-law scientific explanation is to find a logical connection between a phenomenon and an underlying law. The ideal case would be a law that allows prediction of the phenomenon as soon as all of the relevant initial conditions are known. It is important to highlight that scientific explanations should fulfil two quality criteria: (1) they should be logical and (2) they should explain the occurrence of various phenomena with the combination of a set of specified initial conditions and a single (or, in some cases, more than one) general physics law.

Instructional explanations, however, have a different character. Treagust and Harrison (1999) were among the first to point out the importance of this difference for science teaching. The main quality criterion for an instructional explanation is that it focuses on and effectively addresses the needs of an addressee (*explainee*) and makes it possible that someone makes sense of the information. Logic is certainly helpful for attempts to meet this goal, but it is not a sufficient condition. Just as important are characteristics of the explainee such as prior knowledge, possible misconceptions or areas of interest. There are even studies suggesting that explanations that primarily focus on an explainee's prior knowledge are more likely to be successful than those following a logical content structure (Nathan and Petrosino 2003).

The difference between scientific explanations and instructional explanations can, however, also be found in their structure. In the case of scientific explanations, one could say that the general law explains the occurrence of a phenomenon. In the case of instructional explanations, it is often the case that the general law is, at least in one sense, something mandated by a syllabus or curriculum that students are required to come to understand and to be able to demonstrate their understanding in an assessment task. Explaining, in this case, mostly means showing that this general law has the power to explain different phenomena that appear to be very different at first sight. Thus, in science teaching, explaining often works in the reverse order to scientific explanations: It is not that the law explains the occurrence of the phenomena, but that different phenomena are used to illustrate a law. These phenomena play the role of examples; and the choice of examples has a major influence on the comprehensibility of an explanation.

Finally, the process of explaining needs to be distinguished from its product, the explanation. Intending to *engender comprehension* (Gage 1968), we must make an important but somewhat disillusioning statement: There is no such a thing as an ideal explanation for everyone. Explaining is an active, interactive and communicative process of developing candidate explanations, delivering them to explainees, testing for their comprehension and gaining their feedback, and then further modifying the explanation with the goal of enhancing the explainees' comprehension. Explanations play the role of recurring *products* in this process. Diagnosis and feedback lead to a gradually improved mental model in the mind of the explainer with respect to these explainees' needs and what can help them to construct meaning and understanding of the target information. How this process should be designed is described in Sect. 12.5. First, however, we need to understand why there are criticisms of the use of explaining in science teaching and why these criticisms highlight some very important issues in relation to explaining in science classrooms.

12.3 Criticisms of Explaining in Science Teaching

Instructional explanations by teachers have a little bit of a shady reputation. One important reason for this may well be that instructional explanations and scientific explanations are often mixed up by explainees, and instructional explanations are inappropriately judged using the standards appropriate for scientific explanations. It is a common misunderstanding that instructional explanations are simply scientific explanations that are reduced in complexity and somehow *covered with a shiny surface* that makes them understandable to explainees. We want to make it very clear that this is not the case. This misunderstanding is also present in the research literature.

There were studies that used the term *explaining* deprecatingly and equate it with a strong teacher-centred teaching or merely a presentation of scientific facts with no interaction (e.g. Chi et al. 2001). Indeed, explaining in this sense—of the attempted direct transmission of content knowledge from the mind of the explainer to that of the explainee—is not part of good teaching at all. One message should be clear: It is a misunderstanding to think that the secret of good explaining is finding a maximal understandable representation of content matter and that this will lead an explainee to understand an explanation automatically. This so-called *transmissive view* of explaining contradicts fundamental research findings about how learning works as the construction of meaning by learners based on their existing knowledge and their new experiences.

Explaining, however, can be understood based on constructivism (Geelan 1997) as well. The goal of explaining should be seen as the provision of experiences—including words from the teacher—increasing the likelihood that an explainee can construct meaning from an explanation. We can even show empirically that teachers who equate explaining with lecturing explained significantly less efficiently compared to teachers who acknowledged that explaining is a process targeting an explainee's knowledge construction (Kulgemeyer and Riese 2018).

It has been shown many times that learning works if students construct meaning based on their preconditions, most importantly their prior knowledge; this concept is at the core of constructivism itself. That insight may seem to contradict any justification for instructional explanations and support always having students construct their own understanding based on their experiences (in physics, either past experiences they can recall or the special category of experiences we call *experiments*)—but only at first sight. There is no need for students to just passively receive an instructional explanation. Good explaining is rather designed to avoid this. Good explaining aims at activating students and supports them to build mental models of the explained matter.

One might wonder whether there is another reason for the bad image of instructional explanations. Students might be activated cognitively during an explanation but cognitive activation should not be confused with physics activity. Physics activity can nearly always be observed in self-organized learning environments, whereas cognitive activation cannot be directly observed and must be inferred. Studies even showed that physics activity is not supportive for students' achievement but cognitive activity is (e.g. Skuballa et al. 2018). Indeed, the same quality criteria apply to self-organized learning environments and to instructional explanations. Cognitive activation is the most important of such criteria. In a nutshell, we can safely assume that instructional explanations in science teaching are often confused with teacher-centred lecturing even though they fundamentally differ from lecturing in a very important way: If they are designed properly, instructional explanations are interactive, aim at diagnosing misunderstanding and, at the same time, provide structures for the development of complex concepts that most students probably cannot simply discover on their own.

Interestingly, teachers' instructional explanations are not perceived as poor teaching by their students. For example, Wilson and Mant (2011) found that the ability to explain well is the one attribute in which exemplary teachers differ most from average teachers from their students' point of view. However, these exemplary teachers do not mention their explaining skills as a positive feature themselves. The reason, again, might be that they confuse interactive explaining and a teacher-centred presentation of scientific facts.

We also want to highlight the fact that students also explain regularly in science teaching, for example, in cooperative learning or when they present results of their work to the class. It might be important to teach them how to explain. Modelling on the part of teachers, as well as explicit attention to the skills of explaining, is an important part of that teaching; and attention to students' explaining skills may even increase the efficiency of cooperative learning (Kulgemeyer and Schecker 2013).

To sum up, criticism of teacher explanations is justified if explaining is understood as meaning nothing more than teacher-centred lecturing. This kind of poor and one-way explanation should be avoided. Explaining just makes sense in science teaching if the focus is shifted from the content structure of the discipline to the explainee's needs, and if explaining is performed as an interactive process in which learners and teachers both actively participate.

12.4 What Makes Instructional Explanations Successful? Seven Core Ideas of Explaining for Understanding

Much empirical work deals with efficient instructional explanations, mostly within psychology but also in science education research. In a critical meta-analysis of this research, Kulgemeyer (2019) identified seven core ideas for developing and delivering efficient and effective instructional explanations. Which of these core ideas is most relevant for which topic in physics teaching is determined by the type of content to be taught and the characteristics of the explainees (Geelan 2020).

12.4.1 Core Idea 1: Focus on the Explainee and Adapt to Prior Knowledge and Interests

The empirically best justified claim in relation to instructional explanations is probably also the most convincing: In order to be successful, instructional explanations should be oriented to the needs of the learners (Wittwer and Renkl 2008). Needs include interests, misconceptions and other characteristics of thinking. In particular, prior knowledge on the part of the explainee is crucial. That is, somehow, not surprising. Of course, someone who is unfamiliar with the terms and mathematics of quantum physics will have problems following a mathematical explanation of the Franck-Hertz experiment. The challenge, therefore, is to find a common ground for communication, to express things differently and to adapt to the explainee's prior knowledge. That is a tough challenge, indeed!

It may be more surprising that empirical research shows as that it is not a promising strategy to explain as simply as possible and to avoid all mathematics and physics diagrams. That is because an *expertise reversal effect* (Kalyuga 2007) has also been found in research on instructional explanations. That means that some explanations that are comprehensible for novices are unnecessarily complicated for experts and, therefore, less effective. An explanation for this effect comes from cognitive load theory (e.g. Sweller 1988). Including a summary, for example, can be helpful for novices, whereas this is an unnecessary repetition for experts. Unnecessary information is cognitive load that prevents the explainee's cognitive capacities from dealing with the relevant parts of the explanation. This effect is the same for the explanations offered in textbooks: If explanations follow criteria for text comprehensibility they become more comprehensible for novices, and at the same time less comprehensible for learners with higher prior knowledge (McNamara and Kintsch 1996).

That is another reason why there is no such thing as an ideal explanation for everyone. It very much depends on the individual's state of knowledge as to what becomes unhelpful cognitive load and what is of necessary help to increase comprehensibility. It also shows that two parts of a teachers' professional knowledge are of importance when it comes to good explaining: (1) profound knowledge about which knowledge can be expected from a learner (including knowledge of possible misconceptions and the curriculum) and (2) diagnostic skills to refine their assumptions about this knowledge. Good teachers, indeed, can diagnose learners' state of knowledge accurately and vary their explaining approach accordingly (Duffy et al. 1986). Regarding the first point—teacher knowledge about the students—it is important to highlight that studies showed that explainers often think the explainee has a much higher prior knowledge than is actually the case (e.g. Nickerson 1999). Furthermore, explainers with a high level of content knowledge often expect a much too high content knowledge level on the part of their explainees. This leads to an unexpected effect: Sometimes, experts with very high content knowledge explain less effectively than people with lower content knowledge because they do not adapt well to the explainees' needs (Kulgemeyer 2016). Studies also showed that pedagogical content knowledge (PCK)—particular knowledge about misconceptions and instructional strategies—mediates the influence of content knowledge (CK) on explaining quality. In other words, PCK makes CK useful in explaining (e.g. Kulgemeyer and Riese 2018) and can mitigate the issue where a high level of content knowledge on the part of the explainer makes the explanation less effective.

Besides meeting explainees' cognitive prerequisites, adaptations of the explanation to their interests are also important (Kulgemeyer and Schecker 2009). Among other things, this consideration—what explainees will find interesting—heavily influences the choice of examples to illustrate the topic being explained.

The idea of adapting the explaining activity to the explainees' prerequisites, however, is very abstract. How do we reach this goal? The next section describes four means towards adaptation: a handy toolbox that is helpful in successful adaptation.

12.4.2 Core Idea 2: Use Means for Adaptation

Adaptation to the learners' prerequisites and characteristics requires means to reach this goal. Profound knowledge of this toolbox is essential for good explainers. There are, basically, four areas that allow adaptation (Kulgemeyer and Schecker 2009, 2013):

1. Language level
2. Examples and analogies
3. Level of mathematization
4. Forms of representations and demonstrations.

Explainers can imagine these four means as tools that, when used skilfully, allow them to find the correct adjustment for all of the explainees' prior knowledge, misconceptions and interests. Indeed, an individual adjustment applies only to each individual, and it is even more of a challenge to explain to a whole class and to find a good balance. The core part of the process of explaining is to adjust in relation to each of these four means in order to reach a better adaptation of the explaining process (and the explanation product) to the explainees.

Adapting the language level to explainees' needs might mean replacing technical terms with everyday language but that depends on explainees. It might also mean that it is better to use technical terms for some explainees. The pragmatic rule of thumb for instructional explanations at school is to use a limited set of (new) terms and to critically evaluate which terms are really needed. Yager (1983) found that many secondary school science textbooks introduce more terms in the new vocabulary in a year than foreign language learning textbooks at a comparable level of schooling. For the German language, there is research showing that numerous technical terms in physics textbooks are used only once (Merzyn 1994). Whether or not a technical term is needed should be evaluated from a curricular perspective with consideration of connectivity to the following topics and a physics point of view about correctness, as well as in terms of the technical vocabulary mandated by the syllabus.

There is danger in a strategy that can be observed regularly on the part of inexperienced explainers. If they realize that explainees did not understand, they change the concepts they use for the explanation. This also leads to a whole new set of technical terms. Kulgemeyer and Tomczyszyn (2015), for example, videotaped preservice science teachers explaining to students why blowing up an asteroid changes the trajectory of all of its pieces. When confronted with student misunderstandings, they reacted by changing the focus concept and talked about forces or energy instead of momentum. In general, this is not supportive and does not aid comprehension. Explainers should stick to the chosen concept except if they realize that the concept itself cannot be understood by the learners, in which case it may be necessary to revise some necessary concepts from those used earlier in the course or earlier in the explainees' education.

Adapting examples and analogies to the explainees' prerequisites is quite similar to adapting the language level to their needs and is probably one of the most important parts of explaining in general. Examples in studies (e.g. Duit and Glynn 1995; Clement 1993) showed how an explained concept applies and supports individuals' understanding of how a general concept solves a range of problems that appear very different at first sight. Analogies (and also metaphors and even models) bridge the gap between the new, unfamiliar topic and an area that has already been understood. Duit and Glyn, as well as Clement, showed that something new behaves (in parts) like something already known. Here, sometimes explainers use anthropomorphisms, which are analogies between physics and human behaviour. For example, an ideal gas is sometimes illustrated by a moving crowd. Anthropomorphisms are sometimes judged critically because free will is limited to humans whereas physics applies to inanimate matter. They can, however, also support understanding because human behaviour is familiar to all learners. The same goes for any kind of models: The limitations and the point where the analogy breaks down—with the features of the familiar concept no longer map to those of the concept being explained—have to be made clear.

The level of mathematization also needs to be adapted. No doubt, mathematical expressions of laws require verbal explanations as well. However, physics theories require efficient mathematical expressions as well: To avoid mathematics, in general, would be a mistake and shows a dubious picture of physics from a nature of science point of view. Geelan (2013), in a study observing experienced teachers, described the *move to mathematics*, in which teachers typically began with qualitative explanations or demonstrations and then moved to equations and calculations during a lesson. Drawing on an appropriate level of mathematics for student knowledge is also important. In some contexts in secondary school physics, some students within the class will have studied calculus, whereas others have not; and therefore, explaining needs to be adapted to the knowledge and skills of all students.

Forms of representations and demonstrations are helpful tools for adaptation if they support verbal information in the sense of dual coding. Forms of representations can include graphs of any kind, diagrams, photos, animations and simulations or even videos. Demonstrations have an important place in instructional explanations if they show an explained example as a model.

12.4.3 Core Idea 3: Highlight Relevancy and Use Prompts

Empirical research shows that the perceived relevance of an instructional explanation influences student achievement. This is especially the case if an instructional explanation is performed by the teacher in response to a misunderstanding on the part of a student or after a topic has been dealt with in class. Perhaps surprisingly, in this case, students tend to perceive further explanation as redundant and irrelevant (Acuña et al. 2011). The following simple approach is a promising candidate to solve this problem. In a study by Sánchez et al. (2009), it was sufficient to highlight at the beginning of the explanation of a topic that the explanation deals with a common misunderstanding and the teacher has chosen to present it because many people hold misconceptions about the topic. That reminds both teachers and students that teaching strategies can and should be chosen to deal with misconceptions and promote conceptual change.

The most important strategy of a successful explanation—(a) to show that an explanation is relevant to the students and (b) to signal which part of an explanation is particularly important—is called *prompting*. Prompts are explicit signals (Diakidoy et al. 2003) such as "this point is especially important because many people understand this wrongly" or "many people think about energy as something like a material—but is that appropriate?" Roelle et al. (2014) showed that these kinds of prompts affect students' achievement. The reason is probably that prompts affect the explainees' perceived relevance of the explanation, which in turn leads to their cognitive activation instead of passive listening.

12.4.4 Core Idea 4: Give It a Structure

The structure of an explanation has been discussed especially in the context of scientific explanations but structure is important for instructional explanations as well. Firstly, a clear structure helps to make relationships explicit for both explainers and explainees. It is very helpful to have a clear picture of an explained topic in order to build a coherent mental model. There is even research that examines the effects of different structures (e.g. Seidel et al. 2013). For example, two structures are compared directly: starting an explanation with a presentation of the general law and later illustrating it with examples (rule–example structure) or, vice versa, starting with examples and later deducing the general law from them (example–rule structure). The efficiency of these structures depends on the goal of the explanation. If the goal is the acquisition of content knowledge, an explanation with the rule–example structure seems to be superior (Seidel et al. 2013). However, if the acquisition of practical skills is the goal, an explanation with an example–rule structure outperforms one using a deductive approach (Seidel et al. 2013). What does this mean for teaching physics? If the learning goal is Newton's third law, it is appropriate to start with an explanation explicitly and later show different examples that illustrate how the law works. If the learning goal is to learn how to solve specific problems (e.g. by using a force or an energy approach), it is appropriate to start with a worked example and later present the underlying principle that justifies the approach. It is also important in this case, however, that the general principle is mentioned explicitly! Just explaining the steps required for the solution of the problem is not sufficient because it would only help students to understand the solution of this particular task but not help them to learn how every problem of this kind can be solved–they do not learn flexible conceptual knowledge and my even confuse the example (or analogy) with the concept.

That, by the way, does not mean that an explanation cannot start with an example if it aims for content knowledge acquisition. An example at the beginning might even help to increase the interest of students. However, the general law should not be deduced from this example; the law should still be given explicitly and later illustrated. The teacher may say, “What we just saw can be explained with Newton’s third law—and this is what the law looks like”.

12.4.5 Core Idea 5: Explain Precisely and Coherently

An explanation should be coherent and minimal, meaning that it should stick to what is important and leave out irrelevant details (Anderson et al. 1995). Coherence and minimalism are related to one another. Coherence as a characteristic of good explaining has been researched, especially in the context of textbooks (e.g. Wittwer and Ihme 2014). The underlying thought is that it helps students to build a mental model of an explained topic if the connection between elements of the topic is clear. That includes good connection of sentences, for example, by using the same terms in two sentences instead of using pronouns or synonyms. It already requires a certain knowledge of a topic to understand that two different words signify the same term and have the same meaning. For novices, two different words would appear as if they had two different meanings and it requires their cognitive capacities to clarify that: cognitive capacities that would have been useful in order to understand the subject matter! Also, connections between sentences can be highlighted by using connectives such as *because*. That helps explainees to understand what the phenomenon of interest is and to what general law it is connected.

Avoiding irrelevant details in an explanation is important because it helps explainees to focus their cognitive capacities on its relevant parts. Digressions should also be avoided (Renkl et al. 2006). Novices simply cannot know which part of an explanation is relevant and which part is extra information. In a nutshell, an explanation should be minimal and show the explained topic clearly. Later, new information may be added, especially if students ask for it.

Some researchers suggested that a good explanation should be built like a good story (e.g. Ogborn et al. 1996), in that it has a beginning that sets up expectations, a middle part that complicates them and an ending that resolves them. That really can have an advantage because a good story leads the audience to sympathize with the protagonist, increasing the perceived relevance of the explanation. It might, however, seduce the explainer into giving too much irrelevant information and that would result in reverse effects. Explainers should be careful to focus on the most salient details of their explanations.

12.4.6 Core Idea 6: Explain Concepts and Principles

Renkl et al. (2006) suggested that an explanation should address only concepts and principles. There is certainly something worthwhile in that suggestion. Understanding a principle means realizing that superficially very different problems can be reduced to the same idea and explained by the same approach. Explaining physics as a science is very efficient in doing so. There is also empirical research that supports this view. Dutke and Reimers (2000) showed that it is more effective to explain a principle than to show the solution of a problem step by step.

Knowing principles is an important goal of physics education. Therefore, if teachers want to use instructional explanations, they should do so, especially if their learning goal is for content knowledge acquisition rather than the development of skills. It is obvious, anyway, that, for example, experimental skills cannot be acquired by instructional explanations but must be developed in laboratory or other experiences.

12.4.7 Core Idea 7: An Explanation Should Be Embedded in Teaching

The last core idea refers to the notion that explaining is a process and not a product. An instructional explanation (the product of an explaining act) should be embedded appropriately in teaching. Explanations are not teaching in themselves, but they are just a part of teaching. Teaching includes diagnosis of understanding as an important part of the development of the explanation and as a prerequisite for further adaptation. Instructional explanations also should not replace cognitive activities. Learning is something only the learner can do; therefore, it cannot be replaced by an instructional explanation even if the explanation has an extraordinary quality. There is research on the question of the circumstances under which self-explanations (i.e. students engaging directly with physics phenomena or their representations and seeking to construct understanding for themselves) are more efficient than instructional explanations for constructing understanding. In principle, it is easier to reach high cognitive activation with self-explanations. That is why some researchers regard instructional explanations merely as a supportive means towards the process of self-explaining. However, there is an important problem with self-explanations. Students tend to interrupt self-explaining activities when they think they have understood a topic.

However, that is not always the case: They sometimes just think they have understood the topic, even though they have not (for the so-called *illusion of understanding*, see for example Chi et al. 1989). The well-known Dunning–Kruger effect is the fact that novices are not well positioned to make judgements of their own understanding (Kruger and Dunning 1999). After instructional explanations given by a teacher, it might also be the case that students' understanding of a topic is more superficial than they think, but the teacher has a certain level of control over this situation. He or she can diagnose their understanding and react to it accordingly. In particular, topics that include common misconceptions might be vulnerable to an illusion of understanding. A lot of common misconceptions about scientific concepts are very effective in predicting everyday phenomena and self-explanations might even strengthen these misconceptions rather than leading to conceptual change.

The clear advantage of self-explanations is their potentially high cognitive activation. However, instructional explanations can also reach high cognitive activation. To do so, they should be embedded in ongoing cognitive activities and not replace them (Wittwer and Renkl 2008). But how? A good instructional explanation initially leads to learners being able to memorize and comprehend the content of the explanation itself (declarative knowledge), for example, Ohm's law. Being able to use this knowledge to solve novel problems—that have not been part of the content or context of the explanation—requires of learners to use a different kind of knowledge or more flexible conceptual knowledge. Instructional explanations are not very useful tools in terms of providing this kind of knowledge (Kulgemeyer 2018). That is why instructional explanations should always be followed by learning tasks that require learners' autonomous application of the explained concept to solve new problems (Altmann and Nückles 2017). Studies showed that the quality of these learning tasks is at least as important for achievement as the instructional explanation itself (e.g. Webb et al. 2006). The criteria for well-designed learning tasks that foster cognitive activation can be found in Chap. 9 of this book.

Cabello and Topping (2018) proposed another promising approach to embed instructional explanations successfully into teaching. They propose looking for synergies between learners' and teachers' ideas by contrasting the students' ideas with the explanation. This indeed might lead to students' questioning a teacher's explanation and an improved co-construction of knowledge.

12.5 When Should I as a Teacher Explain and When Should I Avoid It?

As mentioned above, explaining has often been seen as an ineffective and outdated form of teaching. From the core ideas and empirical research outlined in this chapter, it follows that this is not always true. There are conditions under which instructional explanations are promising tools for learning and also conditions under which a teacher should rely on different forms of teaching.

Two *starting conditions* should be fulfilled if a teacher wants to use instructional explanations effectively:

1. Instructional explanations should focus on laws or principles. That is a starting condition from a physics point of view. Even if the occurrence of phenomena is being explained or if the goal is to show how a certain type of problem can be solved, the underlying principle should be stated and connected to the explanation.
2. There are prerequisites of the learners that determine whether instructional explanations offer a promising approach to teaching a particular concept. These are starting conditions from a pedagogical content knowledge point of view. It seems to be the case that, given a high level of content knowledge on the part of the students, self-explanations are the better choice. Instructional explanations have their place at the beginning of a teaching sequence when principles are first being introduced. This is especially the case if there are many common misconceptions in relation to the explained principle. Considering this starting condition, we suggest a side note here: It seems odd that there is a tendency in the educational system in which the higher the content knowledge level that the learners already have (e.g. university majors compared to high-school students), the more the teacher shifts towards teaching forms that contain instructional explanations.

An example that fulfils both starting conditions is already given in the introduction of this chapter: the introduction of Newton's third law. It is a principle that can be illustrated by many examples from everyday experience. There are many known misconceptions on this law (e.g. it is often confused with an equilibrium of forces) which makes it difficult to develop this principle through self-explanations. When Newton's third law is being introduced in physics, instructional explanations are a promising tool.

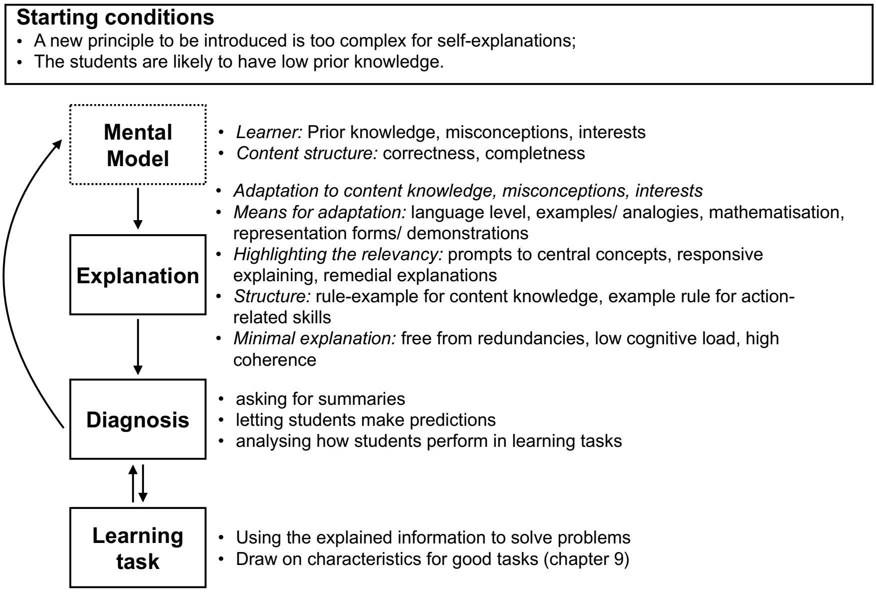
Skills in solving problems by calculating the amounts of different forms of energy present before and after a process is an example of something that should probably not be the subject of an instructional explanation. When it comes to solving a certain kind of problem or task, learning with worked examples is the better choice. If a verbal explanation was offered in this context, it would not aim at supporting the development and comprehension of a concept (except for the goal being an explanation of the conservation of energy), but rather at supporting skills for calculation, corrections of common calculation errors and perhaps ways to conduct calculations more efficiently in an examination. It is also likely that such an explanation would be performed after conservation of energy as a principle has been introduced, when a certain level of prior knowledge could then be expected. Both starting conditions for instructional explanations are not fulfilled in that case.

12.6 A Guide to Planning Instructional Explanations

The seven core ideas and the two starting conditions can now be summarized to form something like a guide to planning and conducting instructional explanations. The guide contains guidelines based on the current state of research; however, future research might lead to further refinement. Figure 12.2 shows this guide as a representation of the process of explaining in science teaching and all its steps.

Of course, the process starts with consideration of the starting conditions. Instructional explanations have their place in a teaching sequence if a new principle is to be introduced that is too complex for self-explanations and likely to contain misconceptions. The learners should also have low prior knowledge of this content.

After these considerations, the explaining starts. Planning an explanation is based on a mental model about the learners' prerequisites and the content structure. An explainer should have sound ideas about the learners he or she wants to address, especially those about their state of content knowledge and possible misconceptions. An explainer should also know the content structure well enough to identify the important parts that the explanation should contain. This mental model serves as an initial orientation for the explanation but the explanation is further refined iteratively in the process of explaining, seeking feedback from or testing for comprehension of the explainees and then, this is followed by further explaining. For example, the part of the explainer's mental model that is about the explainees' state of content knowledge is further refined after the explainer realizes that certain points of the explanation have



Starting conditions

- A new principle to be introduced is too complex for self-explanations;
- The students are likely to have low prior knowledge.

- *Learner:* Prior knowledge, misconceptions, interests
- *Content structure:* correctness, completness

- *Adaptation to content knowledge, misconceptions, interests*
- *Means for adaptation:* language level, examples/ analogies, mathematisation, representation forms/ demonstrations
- *Highlighting the relevancy:* prompts to central concepts, responsive explaining, remedial explanations
- *Structure:* rule-example for content knowledge, example rule for action-related skills
- *Minimal explanation:* free from redundancies, low cognitive load, high coherence

- asking for summaries
- letting students make predictions
- analysing how students perform in learning tasks

- Using the explained information to solve problems
- Draw on characteristics for good tasks (chapter 9)

Fig. 12.2 Explaining as a process in physics teaching not been understood. It is worthwhile to acknowledge that it is highly challenging for a teacher to build such an accurate mental model. Many resources influence this mental model, and it is particularly important for it to hold both profound content knowledge and pedagogical content knowledge (Kulgemeyer and Riese 2018).

In a narrow sense, what follows after checking that the topic meets the initial conditions and developing a mental model—about both the explainees' prerequisites and the content—is a first attempt to explain the content in the explanation. The seven core ideas are very important for developing and refining an explanation. Adaptation to the learner's prerequisites can be achieved by using the four adaptation levels of (1) language, (2) examples/analogies, (3) level of mathematization, and (4) forms of representations/demonstrations. Also, the most important parts of the content should have been identified and prompts should be integrated such that they can be used to make clearer to the students what these important points are. Students, for example, should be aware of why the explained concept is relevant either to physics itself or to everyday experiences (or to passing a physics exam, but arguably this is a less motivating kind of relevancy); they should also know what kind of problems can be explained using this concept. It is important to involve students actively in the explanation, for example, by addressing them directly with *you* or by using questions they need to think about. These kinds of prompts and questions require sound preparation; it is very challenging for teachers to integrate them spontaneously.

Also, the structure of the explanation requires preparation. High coherence is important. The focus should be to avoid the use of synonyms and to connect the law and the examples with *because* or other causal connectors. For the acquisition of content knowledge, a modified rule–example structure is promising because it might help to increase the explainees' interest:

1. Using an example that shows why the principle is relevant and prompting that this example can be understood through understanding the following principle.
2. Naming the principle explicitly and explaining it.
3. Testing the principle by applying it to various examples and by explaining the first example.

The last important core idea includes using little or no digression and repetition, even in the form of a summary. It is recommended for teachers to bring along their notes of the planned explanation into the classroom. Even very experienced explainers are not as effective in ad hoc explanations as they could be in well-planned ones (Kulgemeyer and Schecker 2013).

After the initial explanation, there necessarily follows a diagnosis of understanding. Some tools for diagnosis could be to ask the students for summaries or to predict a phenomenon based on the explained principle. This diagnosis helps to refine teachers' mental model about the learners' needs and leads to a better adapted explanation. Teachers check formally and informally for both engagement (i.e. cognitive activation) and comprehension on the part of their students. Before moving onwards, it is important to ensure that all students have an understanding of the topic.

Ideally, the diagnosis is strongly connected to the following phase, the learning task. This should require students of using the explained principle in a self-guided way to solve new problems or to explain a new example. The criteria for learning tasks should be considered (see Chap. 9 of this book). How the students perform in this learning task can also serve a diagnostic purpose, leading to a better refined mental model and, finally, to a better adapted explanation.

According to Kulgemeyer and Schecker (2013), the following ten rules make the explained core ideas more approachable, when the explainer:

1. prepares the explanation (that means that during teaching, teachers should sometimes just say that they will answer this question in the following lesson),
2. illustrates the verbal language with visual forms of representations,
3. involves the students in the explanation by addressing them directly (which sometimes turns an instructional explanation into a dialogue),
4. asks frequently whether or not the students can follow the explanation,
5. answers questions briefly and precisely,
6. uses examples or analogies to connect the new topic with the content already familiar to the students,
7. considers the students' prior knowledge, misconceptions and interests,
8. highlights the relevant parts,
9. gives enough opportunities for students to ask questions and
10. follows a sound structure (e.g. rule–example structure).

Also helpful in teacher education is the use of the rubric of explanations for formative assessments developed by Cabello and Topping (2018). It allows direct feedback that might be very supportive for pre-service teachers.

12.7 Explanation Videos in Physics Teaching

An increasingly important special case of instructional explanations are explanation videos. They are accessible online on different platforms—most prominently YouTube—and there are numerous explaining videos for all common topics of school physics. Students watch these kinds of videos for several reasons, including entertainment and preparation for exams, but explaining videos are also increasingly part of formal learning (Wolf and Kratzer 2015). For example, in flipped classrooms, teachers give students access to videos (or even produce them for their students), assigning to students the task of watching them at home and answering related questions. Later, in the classroom, the students work on learning tasks concerning the explained topic, supported by the teacher. Producing explaining videos together with the students can also be a powerful tool for learning, especially at the end of a teaching sequence. Furthermore, producing an explanation video is an interesting tool not *just* because it requires students to understand the physics content and edit the video accordingly but also because it requires teachers' considerations about the explainees—an important part of science communication competence (Kulgemeyer and Schecker 2013). Having the students think about the audience to whom their explanation is directed—their peers, younger students, parents or members of society more broadly—involves them in a metacognitive process of modelling the thinking of others (see Table 12.1).

It is, however, an interesting question whether or not the quality criteria for good explaining can simply be applied to explaining videos. Of course, the medium is important and, for example, the cognitive theory of multimedia learning (Mayer 2001) surely adds to them valuable ideas. The most important difference between explanation videos and instructional explanations is certainly the problem of adaptation and audience. Whereas good instructional explanations are interactive and enable the explainers to revise their mental model about the learners and change their explanation attempts accordingly, explanation videos (not unlike explanations written in textbooks) are a static product. That makes it even more important to know the audience very well before producing a video, as well as when teachers produce videos together with their students. It is an important step to take enough time to write a profile of the audience and a script.

Kulgemeyer (2018) adapted the core ideas for instructional explanations to the specific context of explanation videos and developed a framework for potentially effective explanation videos. This framework has successfully been used to develop and analyse explanation videos (see Table 12.2).

Kulgemeyer and Peters (2016) used a similar framework to analyse explanation videos on YouTube and found that none of the quality criteria available on YouTube (e.g. Likes, Clicks, Dislikes) predicted explaining quality appropriately. It may not be very surprising, but these superficial measures are not helpful for teachers if they want to find a good video for their students. Furthermore, research suggests that the developers of YouTube videos do not aim for high explaining quality because that is not what makes a video successful (in terms of clicks)—the popularity of a

Table 12.1 Potential use of explanation videos in science classroom (Kulgemeyer 2018; Wolf and Kulgemeyer 2016)

		Producer of explaining videos	
		Teachers	Students
Explainee	Teachers	Teachers learn from other explaining experts how to explain a particular topic (e.g. good examples)	Teachers use students' explanation videos as an alternative form of assessment
	Students	Students learn from expert explainers, giving them access to an additional explaining approach compared to their own teacher's Teachers develop explanation videos for their own students and use them in flipped classroom settings	Students produce explanation videos; teachers assist them by giving feedback on (a) scientific correctness and (b) appropriateness of videos for a particular group of interest; and learning opportunity for (a) content knowledge and (b) communication skills

Table 12.2 Framework for effective explanation videos (Kulgemeyer 2018)

Factors	Feature	Description
Structure	Rule–example, Example–rule	If the learning goal is factual knowledge, the video follows the rule–example structure If the learning goal is a routine or procedural knowledge, the video follows the example–rule structure
	Summarizing	The video summarizes the explanation
Adaptation	Adaptation to prior knowledge, misconceptions, and interest	The video adapts the explanation to a well-described group of addresses and their potential knowledge, misconceptions, or interests. To do so, it uses the “tools for adaptation”
Tools for adaptation	Examples	The video uses examples to illustrate a principle
	Analogies and models	The video uses analogies and models that connect the new information with a familiar area
	Representation forms and demonstrations	The video uses representation forms or demonstrations
	Level of language	The video uses a familiar level of language
	Level of mathematization	The video uses a familiar level of mathematization
Minimal explanation	Avoiding digressions	The video focuses on the core idea, avoids digressions and keeps the cognitive load low. In particular, it avoids using too many “tools for adaptation” or summaries
	High coherence	The video connects sentences with connectors, especially *because*
Highlighting relevancy	Highlighting relevancy	The video highlights explicitly why the explained topic is relevant to the explainee
	Direct addressing	The explainee is getting addressed directly, e.g. by using the second-person singular instead of the passive voice
Follow-up learning tasks	Follow-up learning tasks	The video describes learning tasks the explainees can engage with to actively use the new information after the video

(continued)

Table 12.2 (continued)

Factors	Feature	Description
New, complex principles	New, complex principle	The video focuses on a new scientific principle that is too complex to understand by self-explaining, e.g. because there are frequent misconceptions

channel among students depends on very different factors. Even more, developers of explanation videos quite often probably have misconceptions about teaching and learning, or about the content, themselves and are not aware of the quality criteria for explaining.

One result, however, is encouraging: Teachers do not need to watch all of the videos on a topic. A first criterion to sort out videos could be a short look at the comment section. Kulgemeyer and Peters (2016) found that videos in which there is a content-related discussion in the comments have a higher probability of being good in terms of explaining quality. The reason might simply be that users need to have understood something about the content to discuss it. In any case, the number of such comments correlates with explaining quality. Comments that just briefly praise the video are not a good indicator. These kinds of comments tend to depend on the popularity of the channel and not on the quality of a single video.

Explanation videos and instructional explanations given by teachers are interesting to compare. The former often appear as a modern part of science teaching whereas the latter, as mentioned above, have the image of outdated instruction. However, regarding adaptation, instructional explanations even have advantages, whereas explanation videos surely are more powerful for learning with animations and multimedia. The intention of both is also the same: An explanation video is basically a filmed instructional explanation. Their place in teaching, therefore, differs just slightly. This chapter is based on empirical studies on their place in teaching. It certainly is worth it to revive teacher explanations in the sense of interactive, constructivist and communicational attempts. Placing them at an adequate place in a teaching sequence and performing them with high quality is very challenging for teachers and should be part of teacher education. Just as important are the skills to develop explanation videos for and together with students. That might even lead to an updated *culture of explaining* in science classroom where science teachers are aware of how instructional explanations and explanation videos work, what they can accomplish and where their limitations are. If researchers acknowledge that explaining is a part of teaching anyway (and sometimes even a powerful tool), they should acknowledge as well that teaching how to explain is crucial. Teachers are very welcome to train their own explaining skills and to use the seven core ideas given in this chapter to critically reflect on their attempts!

12.8 Additional Literature

Geelan, D. (2012). Teacher Explanations. In B. Fraser, K. Tobin & C. McRobbie (Eds.), Second International Handbook of Science Education (pp. 987–999). Dordrecht: Springer.

> This paper gives an excellent overview of research in science education on instructional explanations of science teachers. It completes the paper of Wittwer and Renkl (2008) by adding an educational perspective.

Kulgemeyer, C. (2019). Towards a framework for effective instructional explanations in science teaching, Studies in Science Education, https://doi.org/10.1080/03057267.2018.1598054

> A critical meta-analysis of the research on instructional explanations, including work from instructional psychology and science education research. The seven core ideas are developed in this paper and it includes the most recent studies.

Wittwer, J. & Renkl, A. (2008). Why Instructional Explanations Often Do Not Work: A Framework for Understanding the Effectiveness of Instructional Explanations. Educational Psychologist 43(1), 49–64.

> A review paper on research on instructional explanations, drawing on studies mostly from psychology. To this date the probably most influential paper in this field of research. The depth of argumentation still is unmatched and it is a highly recommended paper for anyone who wants to learn more about instructional explanations. Science education and science teaching, however, play no role.

Acknowledgements We would like to thank Valeria Cabello (Pontificia Universidad Católica de Chile) and Lilia Halim (National University of Malaysia), who not only carefully and critically reviewed this chapter but also contributed valuable thoughts that helped to improve the quality of this chapter significantly.

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