Teaching Critical Thinking in the physics classroom: High school students think about antimatter

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Abstract. Teaching students the skills that they need for everyday life like Critical Thinking (CT) is the goal of education. Embedding Critical Thinking skills within a content-specific instruction is expected to improve students’ critical-thinking skills. In this article, we present our content-specific instructional design for promoting students’ critical-thinking skills. The target group comprises German high school students of grades 11 and 12. The specific topic of learning modules is antimatter. To design the instruction, we combined the model of “First Principles of Instruction” with our domain-specific interpretation of Halpern’s general definition of Critical Thinking skills. To develop and optimize our instructional design, we use Design-Based Research cycle.

1. Introduction
Living in a democratic society requires citizens who have the ability to think critically [1], for example identify arguments, access the argument independently of their own opinions, evaluate alternative solutions, and assess the risks and opportunities to make good decisions. Despite the importance of Critical Thinking (CT), the studies show that students, as part of citizenship, lack the ability to think critically [2]. Therefore, it is a goal of education researchers and teachers to empower students’ critical thinking skills [1, 3-5] and design a learning environment to give students the chance to practice critical thinking for everyday life [1, 5].

To foster and strengthen critical thinking in the schools and colleges a clear definition of critical thinking is needed [1]. Analysis of different definitions led us to identify a common core between them. All definitions emphasize on applying thinking strategies, like argument analysis, reasoning, and decision making to evaluate statements and actions [4, 6, 7]. In some definitions these thinking strategies and the outcomes of applying them are explicitly mentioned like in [6]. Halpern [6] classifies the relevant thinking strategies as Reasoning, Thinking as Hypothesis Testing, Argument Analysis, Likelihood and Uncertainty Analysis, and Decision Making and Problem Solving. In addition, it is important to distinguish between general CT skills, which require knowledge of everyday life [8], and domain-specific CT skills, which require content-specific expertise [9], e.g. in particular domains of physics. Furthermore, acquiring both general and domain-specific CT skills is expected to be result of embedding CT skills within a content-specific instruction [10].

Searching for an instructional design to teach critical thinking, we found that an instruction should be designed in which the students are asked to think about the world, are expected to be thoughtful and reflective and seek to identify one another’s assumptions [1]. The instruction should also require students to realize a problem and establish their knowledge toward solving the problem [11]. These are some suggestions about how the instruction should look like, but mostly the concrete guidelines about how to design such an instruction are not brought forward. Therefore, the goal should be to
systematically exploit promising proposals to design a content-specific instruction to improve both general and domain-specific CT skills. To this end, many questions arise about the content, the design, and the evaluation of the instruction: what should the course syllabus and materials be? What are the principles of the design of the instruction? Is the instruction indeed developing students’ critical thinking?

To make the instruction content-specific, the domain of particle physics is chosen. Particle physics is an abstract topic. Despite the students’ interest in some topics in particle physics like antimatter [12], there are no concrete guidelines and principles for designing a high-quality intervention in this abstract area to solve complex educational problems like teaching CT skills. Considering this situation, we chose Design-Based Research (DBR) methodology to develop and optimize our content-specific instruction in an iterative cycle of design-enactment-analysis-redesign [13, 14]. As a result, we will identify guidelines for designing a content-specific instruction. These guidelines should be transferable to the other areas of physics e.g. energy or mechanics for designing a content-specific instruction to improve general and domain-specific CT skills.

2. Theoretical framework and research questions

As alluded to before, the different definitions of Critical Thinking (CT) are different in wording but have many aspects in common. For the purpose of this study we found that Halpern’s definition [6] captures the essence of other definitions and is based on the skills that can be tested using Halpern Critical Thinking Assessment (HCTA) [15] in terms of the observable outcomes of applying CT strategies, which are unobservable. Furthermore, studies on the evaluation of the ability concerning CT showed that both general CT skills [8] and domain-specific CT skills [9] should be taken into account.

In addition, fostering the development of students’ CT skills needs a well-designed subject matter instruction [9]. Embedding CT within subject-matter domains has been placed theoretically in the focus of some studies [8, 16]. However, theoretical limitations (regarding instructional design models which develop students’ general and domain-specific CT skills) and lacking empirical evidence (regarding the effectiveness of these models) are still a challenge. Searching for instructional design models that enhance students’ CT skills, we chose to focus on the “First Principles of Instruction” model [17]. It offers guidelines for designing learning environments for higher-order learning outcomes [17]. Being a synthesis of numerous instructional design models, this model has a strong theoretical foundation and five clear principles for designing content-specific instruction: problem-centered, activation, demonstration, application, and integration. These principles can provide students with the opportunity to acquire knowledge and skills that are necessary to complete complex real-world tasks [17]. This model has already been applied in designing a content-specific instruction in Electricity & Magnetism for general and domain-specific CT skills, resulting in the development of domain-specific CT skills [10].

To the best of our knowledge, there has been no research on designing instruction in particle physics where CT skills are trained.

Therefore, we have posed the following research questions:

1. What are the characteristics of an effective instruction in particle physics aimed at acquiring Critical Thinking (CT) skills?
2. How can we design the content-specific instruction to empower students’ general and domain-specific critical thinking (CT) skills?

Here we describe the principles of the design of an appropriate course. The evaluation of its effectiveness is part of an ongoing project.

3. Research Design and Methods

The goal is to design an instruction in particle physics that enhances students’ general and domain-specific CT skills. The specific topic of learning modules is antimatter (10 lessons) and the target group is German high school students of grades 11 and 12.
To design the content-specific instruction, the “First Principles of Instruction” model [17, cf. 10] was combined with our domain-specific interpretation of Halpern’s general definition of CT skills [6, cf. 10 and 18]. To design a high quality intervention, we also considered the criteria of Nieveen [14]: relevance, consistency, practicality, and effectiveness. To develop and optimize our instruction, we use Design-Based Research cycle [13, 14]. We implement the instruction and collect the data from pre- and post-tests, video-recording of teaching sequences, audio-recording of students’ discussions, and students’ answers on the worksheets during the course. From the results of data analysis, we derive appropriate changes in the design of the instruction to improve its effectiveness and practicality and prepare it for the next planned implementations.

In the next section we explain how we applied the “First Principles of Instruction” model and Halpern’s definition to the topic of antimatter to design our content-specific instruction. Furthermore, we describe our methods to fulfil the criteria of high quality intervention in the design stage. The evaluation methods for assessing the quality of instructional design will not be treated in this paper. They were discussed in a paper that is in review process for publishing in the proceeding of the GDCP (Gesellschaft für Didaktik der Chemie und Physik) conference 2018.

Figure 1. Design principles of our content-specific instruction.

4. Course design
Our content-specific instruction was designed based on the “First Principles of instruction” model, Halpern’s definition of CT skills and the criteria for high quality intervention. In the following we will describe how these models combine to form a whole.

4.1. “First Principles of Instruction” model
In designing a content-specific instruction, the model of “First Principles of Instruction” was used as a base of the instruction. This model has five clear principles for designing content-specific instruction: problem-centered, activation, demonstration, application, and integration (Figure 1).

4.1.1. Problem-centered. An effective instruction is one in that learners acquire skill in the context of real-world problems [17]. To fulfil the central principle of problem-centeredness, a problem was identified which related both to particle physics and to students’ everyday lives, and required CT skills. After brainstorming and discussion with particle physicists from IKTP (Institute for Nuclear and Particle Physics) at the Technische Universität Dresden, the fiction movie “Angels & Demons” (2009) was chosen because it features an antimatter bomb. Some scenes of the movie were shown and students were asked to judge if the information in the movie about antimatter is scientifically true. To solve the problem (to be able to judge), students needed some content knowledge and based on their requirements, the outlines of the course were discussed and defined: what is antimatter?, how can be antimatter produced?, how can be antimatter stored?, and annihilation. Through the discussion,
students saw their active role in deciding what they learn and understood the reasons why they learn these topics. They also realized the significant role of having enough and valid information for evaluating statements or everyday news.

4.1.2. Activation. An effective instruction is one in that learners’ prior knowledge is considered as a foundation for the new knowledge [17]. Analysis of high school physics curriculum in Free State of Saxony showed that students in grade 12 are familiar with the conservation laws and center-of-mass reference frame. But we did not take these for granted, we defined some activities to activate students’ prior knowledge, e. g. asking students relevant questions, asking them to apply their prior knowledge step by step to make a ground for establishing new knowledge like applying conservation laws in annihilation and pair production.

4.1.3. Demonstration. An effective instruction is one in that learners observe a demonstration of the skills they need to solve the problem [17]. Since the instruction is expected to enhance students’ CT skills, explicit teaching of general CT skills was designed by defining and illustrating them and planned to be implemented within the first course session. Furthermore, during the course students were asked to focus on purpose, main questions and missing information while doing research or solving a problem.

4.1.4. Application. An effective instruction is one in that learners apply their newly acquired knowledge and skills to solve the problem [17]. As it has been mentioned, the course began with a question: is the information in the movie about antimatter scientifically true? Based on the application principle, the students were asked to apply their new knowledge and skills to offer an individual solution and then group solution toward the problem. Furthermore, the students were asked to complete another task which is related to the topic of the course e. g. medical application of antimatter, Positron Emission Tomography (PET).

4.1.5. Integration. An effective instruction is one in that learners reflect on, discuss and defend their new knowledge and skills [17]. In the end of the course, students were asked to write a scenario for the scene of the movie based on the scientific information and present their work to the class. Here questions for the discussion round are planned to challenge students’ knowledge.

Figure 2 shows a summary of students’ activities based on the “First Principles of Instruction” model.

Figure 2. Applying the “First Principles of Instruction” model [17] to the topic of antimatter.

4.2. Halpern’s definition
For designing an instruction that promotes both students’ general and content-specific CT skills, we focused on Halpern’s definition of CT skills. We used Halpern’s classification of thinking strategies
and defined some content-related skills in each category and corresponding tasks and worksheets to make these skills domain-specific. Figure 3 illustrates five CT skills and for each one example outcome. Here we explain our method for making these general thinking strategies domain-specific.

4.2.1. Reasoning. Reasoning refers to the skill that helps us to determine whether a conclusion is valid [6]. Here identifying vague terms and making them clear are considered as outcomes of applying this thinking strategy [10]. In our course, the Einstein equation \( E = mc^2 \) is an equation that frequently is used. It was important for us that students distinguish between mass and matter, when they talk about energy transformation, applying Einstein’s equation. Therefore, we emphasized on applying correct terminology in different situations, taught students to be careful about the terms they use and be clear about them.

![Figure 3. Halpern’s classification of Critical Thinking skills and its example outcomes [6].](image)

4.2.2. Argument analysis. An argument consists of at least one reason and one conclusion [6]. Argument analysis refers to the skill that helps us to judge how well reasons and evidence support a conclusion [6]. In our course we designed activities in which students were asked to clearly state the reasons and conclusion, define necessary terms and evaluate if the reasons provide good support for the conclusion. For example, after teaching Rutherford’s experiment we asked students to argue against an alternative atomic model by comparing it with Rutherford’s model and to discuss their differences based on the Rutherford’s experimental data. Figure 4 shows the designed worksheet for activating students’ argument analysis skill.
4.2.3. Thinking as hypothesis testing. This thinking strategy refers to the skill that helps us to make hypothesis and to test its validity [6]. One of the outcomes of applying this thinking strategy is to recognize the need for valid information and adequate sample size [6]. To activate this skill, we planned different students’ activities and asked them to make hypothesis and to test their hypothesis. For example, in teaching the syllabus for “trapping antimatter”, we started to discuss trapping matter. After that we asked students to apply their knowledge and make hypothesis about a possible antimatter trap apparatus, draw a sketch and describe it. Then the students were asked to check their own proposal of antimatter trap against existing systems. Here it was important that students collect enough and valid information to be able to compare and to test their hypotheses.

4.2.4. Likelihood and uncertainty analysis. This thinking strategy refers to the skill that helps us to make good decision about uncertain events [6]. One of the outcomes of applying this thinking strategy is that students learn to consider different factors which influence the event and to estimate the extent to what these factors influence the event while making probabilistic decision [6]. In our course during teaching “positron discovery”, students were asked to provide alternative interpretations of the sign of particle and the direction of particle motion in Anderson’s cloud chamber image and to predict their probability of occurrence. The first goal was that students learn to be brave enough to interpret different possibilities as Anderson did [19], and the second goal was that students learn how to apply their knowledge about conservation laws to evaluate the occurrence of each interpretation.

4.2.5. Decision making and problem solving. The skills used in decision making and problem solving help us to identify and define a problem and evaluate solution paths [6]. Here seeking analogies which is relevant to the problem [6] is one of the desired outcomes of applying this thinking strategy. In our
course, after introducing and discussing Rutherford’s experiment students were asked to design a set-up to support notion of quarks, in analogy to Rutherford’s experiment. It was important that students seek similarities between two experiments, Rutherford’s experiment for discovery of the nucleus and the experiment for discovery of quarks, and realize which modifications are needed.

Figure 5 summarizes examples of desired content-specific outcomes of applying CT skills in our course.

**Figure 5.** Applying Halpern’s definition of CT (Critical Thinking) [6] to the topic of antimatter.

### 4.3. Criteria for design a high quality intervention

Beside applying the model of “First Principles of Instruction” and Halpern’s definition of CT skills, the following criteria [14] were considered to develop teaching sequences and students’ tasks.

**4.3.1. Relevance.** To check the content validity of the instruction, regular meetings with a group of particle physicists and physics educators at the Technische Universität Dresden were organized.

**4.3.2. Consistency.** To check if the tasks and teaching sequences are designed logically, the intervention was screened and discussed with a group of physics educators at the Technische Universität Dresden in different stages of its development.

**4.3.3. Practicality.** To check if the tasks and teaching sequences are expected to be usable in a real setting, criteria such as time, level of difficulty and students’ level were defined. Then in a face to face setting, 8 physics teacher students in the University College of Teacher Education Vienna (Pädagogische Hochschule Wien) together with the researcher went through the set-up of the intervention.

**4.3.4. Effectiveness.** To check if the tasks and teaching sequences are expected to result in the desired outcomes, we developed a Hypothetical Learning Trajectory (HLT) that consists of 3 components: the learning goals, the learning activities and hypothetical learning process [20-22]. Here we explain an example of developing HLT in our course.

**Hypothetical Learning Trajectory (HLT).** As it has been already mentioned, the goal of design of the instruction is promoting students’ general and domain-specific critical thinking skills. To check if the goal of each component of the instruction such as teaching sequences, students’ activities and the course materials meet the goal of the whole instruction, we needed to generate single HLT for each component. As an example, here we describe how we generate a HLT for designing “Anderson’s cloud chamber photograph worksheet” in teaching “positron discovery”.

| Critical Thinking Skills | Description |
|--------------------------|-------------|
| Reasoning                | Distinguish between mass and matter |
| Argument Analysis        | Compare two alternative atomic models based on Rutherford's experimental results |
| Thinking as Hypothesis Testing | Check their own proposal of antimatter trap against existing systems |
| Likelihood & Uncertainty Analysis | Provide alternative interpretations of Anderson's cloud chamber image & predict their probability of occurrence |
| Decision Making & Problem Solving | Design set-up to support notion of quarks, in analogy to Rutherford's experiment |
students the famous Anderson’s photograph and asked students in the first task to make interpretations about the sign of charged particle and the direction of particle motion. Here we assumed that students know Lorentz force and can apply the right hand rule. In the second task students were asked to evaluate the occurrence of each interpretation applying conservation laws. Here we assumed that students know conservation laws. To generate the HLT, we started to identify the learning goals for students [21]. The learning goals were that students:

- apply their knowledge about Lorentz force and the right hand rule (content knowledge) to make interpretations in the first task.
- apply their knowledge about conservation laws (content knowledge) to estimate the probability of occurrence of an event (CT skill) in the second task.
- understand how to use probability judgment to improve decision making (CT skill).
- understand the need for valid and enough information to make more accurate prediction (CT skill).

The next step in the creation of the HLT was generating a hypothetical learning process [21]. Our hypotheses for the learning process were that students will:

- use their knowledge about Lorentz force and the right hand rule and make different interpretations about the sign of charged particle and direction of its motion, for example one can interpret that a positive particle goes upwards, other can say that a negative particle goes downwards, or two opposite particles fly in opposite directions from the middle of cloud chamber.
- use their knowledge about conservation laws and realize that the second and third interpretations can violate energy and momentum conservations.
- discuss and reflect on their activity to realize the importance of having valid and enough information to make accurate interpretations and the importance of probability judgment in making decision.

Based on the learning goals and the hypothetical learning process, the worksheet was designed (the tasks were explained in the first part of this section). These 3 components together made the HLT for this specific topic.

During the design stage we defined several HLTs. The HLTs can be seen not only as the orientation point for the design and redesign of activities in the design phase, but also as a guideline in the data analysis phase [22]. The HLTs give us a clear picture of what we should look for to assess the actual effectiveness of our instruction.

5. Discussion and outlook
We introduced our instructional design for training Critical Thinking (CT) skills within the context of antimatter. The “First Principles of instruction” model and Halpern’s definition of CT skills proved to be applicable in that we could combine the content-related part with the CT-part. The main characteristic is to be explicit about every instructional step which is simplified by use of the models. Concerning the effectiveness, the evaluation still has to be carried out. However, some first results can be indicated.

So far we have implemented the instruction in a first pilot study as a 4-day workshop at the university with 4 high school students. Video-recording of teaching sequences, audio-recording of students’ discussions, and students’ answers on the worksheets were collected during the lessons. We analyzed the students’ answers on the worksheets by comparing them with the HLTs [22]. The findings were triangulated by video and audio data. Based on the results, we changed the preliminary design of the instruction to improve its effectiveness and practicality and prepare it for the second pilot study. The second pilot study was implemented with 25 students grade 12 in a high school in Pirna, Germany. The students’ tasks and teaching activities mentioned here were the results of the data analysis of the
first and the second pilot studies. Teachers can use the proposed activities or the principles of the design offered here to design a content-specific instruction to teach CT skills.

To evaluate acquisition of students’ domain-specific CT skills, we needed to design a specific test in particle physics that requires applying CT skills. In future work, we will present Particle Physics Critical Thinking (PPCT) test as a research instrument to determine the extent to which students have achieved the learning goals.

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