Introducing an innovative approach of teaching the Standard Model of particle physics at high school

Philipp LINDENAU1,2 and Michael KOBEL1

1Technische Universität Dresden, Institute of Nuclear and Particle Physics, 01069, Dresden, Germany
2Technische Universität Dresden, Chair of Didactics of Physics, 01069, Dresden, Germany

Abstract. The role that is assigned to elementary particle physics in high school education differs all over the world. Even within a single country like Germany there are major differences in the depth of discussion. To help teachers to address the fundamental concepts of elementary particles and their interactions and to reduce the subject didactically with respect to the given general conditions, Netzwerk Teilchenwelt has developed teaching material with an innovative didactic spiral approach that points out connections to common contents of physics curricula and is focused on the fundamental interactions of the Standard Model of particle physics and the charges that generate them. This concept is being presented and discussed during in-service trainings for teachers all over Germany. Since 2017, roughly 290 teachers have been trained in at least two-day courses and enabled to teach this approach.

1. Motivation – why to teach particle physics

Particle physics is one of the most emerging fields of physics research and recent achievements have frequently been in the media lately. The discovery of the Higgs particle and the subsequent awarding of the Nobel Prize in Physics to Peter Higgs and Francois Englert in 2013 as well as to Takaaki Kajita and Arthur B. McDonald in 2015 for the discovery of the so-called neutrino oscillations have surely been recent scientific highlights with wide public attention. But especially the research at CERN (European Organization for Nuclear Research) has also regularly caused dystopic concerns, such as the possibility of creating of dangerous black holes during particle collisions at the Large Hadron Collider (LHC) or of abusing the gained knowledge for constructing lethal weapons, as described in the science fiction novel “Angels and Demons” by Dan Brown (2000).

Under the given circumstances, it is hardly possible not to get in touch with particle physics in one way or another, which, of course, also applies to high school students. Therefore, one goal when teaching students about particle physics has to be to enable them to some degree to distinguish scientific facts or possibilities from pure science fiction and to participate in public discussions on this matter. The latter is a central goal in scientific education in Germany [1]. Whether the engagement with particle physics is suitable to increase students’ critical thinking skills is currently under investigation at TU Dresden.

Furthermore, experience shows that especially mysteriously-sounding terms and ideas like dark matter, dark energy and antimatter often arouse students’ interest. Also the fact that in this field of basic research there are many open questions that cannot be answered by the so-called Standard Model of particle physics (SM), the most precise theory we have at the moment to describe elementary particles and the fundamental processes happening in our universe, may motivate students to continue their scientific education after high school to participate in finding answers to them. From this perspective,
particle physics appears to be a good topic to get and keep students interested in physics during high school education.

In addition to that, particle physics offers chances to amplify knowledge that was gained in other topics like electromagnetism, nuclear physics as well as quantum physics. Key concepts of particle physics are well known to students from other fields, as will be further discussed in section 3.

2. Forschung trifft Schule and Netzwerk Teilchenwelt

German physics teachers want or even have to discuss aspects of the SM at school to various degrees. In the state of North Rhine-Westphalia, for example, the SM has recently been added to the core curriculum in a comprehensive way. In order to support teachers, Netzwerk Teilchenwelt, a Germany-wide network of scientists, teachers and also students, has developed different teaching materials, including a textbook on the theoretical background of the SM with didactic suggestions and advice implemented in a spiral teaching approach with consistent terminology.

This material is the basis for in-service teacher trainings and has been developed in close cooperation with teachers. In the following subsections first Netzwerk Teilchenwelt will be described including the main ideas behind the network as well as its most important activities. After that, a detailed view on the teacher training program “Forschung trifft Schule” (Engl.: science meets school) will be given.

2.1. The key ideas and activities of Netzwerk Teilchenwelt

Netzwerk Teilchenwelt was founded in 2010 and since then it has been financed by the German Federal Ministry of Education and Research. In 2017 and 2018 it has been the official German outreach program of the four big experiments at the LHC. Since its founding it has always been a primary goal to take original data from different particle physics experiments to German classrooms. This is done during so-called Particle Physics Masterclasses. In such a Masterclass students become particle physics researchers themselves for one day. Under the supervision of young researchers (mostly PhD students) they analyse data from particle physics experiments such as the ATLAS experiment at the LHC at CERN, or from astro particle experiments, e.g. the IceCube experiment or the Pierre Auger Observatory. In its course, they use tools that are very similar to the actual research tools, such as interactive event displays for particle identification. In this way it is possible to provide an authentic insight into the daily work of researchers in the field and to give the students an idea of the current research questions and how they are approached, which shows to be perceived by the students as it is intended.

During its existence, Netzwerk Teilchenwelt has also developed various options for students to run experiments on cosmic rays and collect data themselves with different types of detectors. Furthermore, Netzwerk Teilchenwelt provides a huge set of data collected with these and other detectors combined with an interactive learning environment and a data analysis interface online at the Cosmic@Web portal.

Motivated students who are interested in particle physics are also given opportunities to do research on the spot at various experiments, including experiments at CERN. Around 60 students per year participate in four-day workshops at CERN. Students who have shown their dedication to particle physics and outreach in the past also have the chance to participate in so-called CERN project weeks, where they do actual research at CERN for two weeks (plus preparation and follow-up) with the aim of writing a paper on their research. In 2017, five students participated in these project weeks at CERN, eight more carried out research projects at other experiments within the network.

To support teachers who want or have to teach elementary particle physics in their classes, Netzwerk Teilchenwelt has developed various teaching materials, which also are the basis for the contents that are covered during the offered teacher trainings. More information on this material is given in the upcoming subsection.

1 http://physik-begreifen-zeuthen.desy.de/offers/cosmic_particles/cosmicweb/index_eng.html
2.2. *Forschung trifft Schule* – in-service teacher trainings

Netzwerk Teilchenwelt has always provided trainings for teachers in the field of particle physics. Since 2017 this has been done to a significantly increased extent within the program “Forschung trifft Schule”. This program is supported by the Dr. Hans-Riegel Stiftung, a German foundation that focuses on scientific education for high school students and teachers.

The program includes three different types of trainings, namely the base trainings, a multiplier school and a summer school. The base trainings usually last two days and are open to all interested teachers and trainee teachers. They are carried out by a permanent team of two to three lecturers with background in particle physics research as well as in physics education, didactics and outreach.

The basis for these trainings is teaching material that has been developed by Netzwerk Teilchenwelt with support from the Joachim Herz Stiftung, another German education foundation, between 2013 and 2018. During the trainings the theoretical background of the SM is imparted and connections to other common contents of high school physics curricula are pointed out. The chosen approach reflects the argumentation and didactic approach given in the core textbook of the teaching material, called “Ladungen, Wechselwirkungen und Teilchen” (Engl.: Charges, interactions and particles) [2] and will be outlined in section 3. Other key subjects of the trainings are research methods and instruments [4] as well as cosmic rays [5]. The contents are mainly taught in lectures that are enriched with exercises that are also intended to be used at school. Thus the teachers have the chance to deepen the lecture contents while getting an overview of selected teaching material that they can directly implement in their classes, like exercises on the identification of particles in bubble chamber pictures [6] and in event displays of modern multipurpose detectors [7].

The second format, a training for multipliers, is addressed especially to teachers with advanced tasks in teacher education. This training is scheduled for three days and offers a more intense interaction with and amongst the participants, which has proved to be very valuable for the reflection and improvement of the trainings and the chosen teaching approach.

The most extensive engagement with particle physics is achieved during a six-day summer school taking place at CERN. The program includes guided tours to experiments and other parts of the research infrastructure, advanced lectures on the theoretical background of the SM as well as on particle accelerator and detector technology held by active CERN researchers. In addition, there is room for the teachers to develop, refine and discuss own teaching ideas.

Since the start of the training program a total of 247 teachers and teacher trainees have been participating in 12 base trainings and two multiplier schools in which the number of participants is limited to 20 respectively. The cooperation with the Dr. Hans-Riegel foundation is not limited in time, but will be continued until the perceived demand of such trainings is not given any more.

3. Outline and key aspects of the teaching concept

In the following subsections the essential ideas of the developed approach will be stated and some key argumentations, which can also be found to some extent in [8], are presented in detail.

3.1. Essential ideas of the chosen approach

Considering the content of German physics high school textbooks and the information we received from teachers prior to the development of the teaching material as well as during our teacher trainings, it is usually focussed on the spectrum of existing elementary particles and the various possibilities to combine them to composite particle systems when particle physics is introduced. This means that the major goal is to present the scheme given in figure 1 as the most important finding we have gathered through particle physics research. Sometimes this scheme even serves as the starting point of the discussion.
Although the spectrum of existing elementary particles is surely an important part of our current knowledge, to focus on it does not seem to be the best approach to point out what the SM is all about and what our present understanding of the smallest objects in our universe is. There are several reasons for this assumption.

Particle physics by nature is a somewhat inconceivable field of physics due to the impossibility of observing the elementary particles themselves directly. The perceived missing link to students’ everyday life gets even more obvious, when we realize that only three of the twelve elementary matter particles in figure 1 (up-quarks \( u \), down-quarks \( d \) and electrons \( e \)) are necessary to describe the stable matter we encounter in our environment. In addition to that, electron neutrinos \( \nu_e \) and their antiparticles emerge in beta transformations, whereas myons \( \mu \) are the most common particles found in secondary cosmic rays near the surface of the earth and even have technical applications in archaeology \[9\]. But concerning all the other elementary matter particles it is not obvious which role they play in particle physics by the scheme itself and therefore, for anyone who starts learning about particle physics, it is not highly motivating to memorize all their names (or even their properties) just for the sake of knowing them.

From the theoretical perspective there is another important aspect to be considered. The spectrum of known elementary particles is a pure experimental finding and not a consequence of our theory, the SM. It is absolutely not understood, why exactly these particles exist and why we observe the specific intrinsic properties. Considering that the SM is the most predictive validated theory we have today to describe the most fundamental objects and processes in our universe, its predictive power must lay somewhere else and to point out, what this power actually is, is an important goal of the developed approach. Considering that, the discussion of particle physics can contribute to the students’ image of the nature of science when it addresses the difference in the quality of knowledge that can be explained or even predicted by an underlying theory to knowledge we have only gathered by observation but do not know the deeper reasons for it.

But what exactly is it, that the SM predicts so extremely well and which concepts play the essential role in this theory of particle physics? It is simply the description of the interaction of matter particles. These interactions depend on certain properties. We will see later what these properties exactly are.

The essential role of the description of interactions can be illustrated by an analogy. When you want to explain to somebody a game, for example football, in a way this person can identify the game or play it, the most important thing to explain is the essential rules of the game. Concerning football, it is completely irrelevant for the game to be identified as football whether eleven or nine players are playing per team, in which formation they play or even to know the names and skills of specific players on the pitch. The players simply must obey the fundamental rules of the game. In this analogy the players stand for the elementary particles and the rules are their possible interactions and the restrictions, for example conservation laws.

In order to describe how particle-interactions take place and which restrictions exist, only a few exemplary elementary matter particles are needed. The knowledge about the interactions can easily be applied later to all other matter particles. Then they can be systematized according to the way they can interact (like in figure 1). This systematization is a result of the observed interactions and particle transformations and therefore cannot be understood without sophisticated knowledge about these interactions.

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2 This picture serves as an example of the presentation of the SM to the general public and can be found in the respective Wikipedia article (https://en.wikipedia.org/wiki/Standard_Model, 14.01.2019)
Considering that, there is a close analogy to the ordering of chemical elements in the periodic table, which is one of the many points of contact to other contents of scholar curricula. One major goal of the described teaching approach and the material as such was to find and emphasize those points and analogies between particle physics and other fields of physics or scientific fields in general. With these connections, teachers will be able to integrate aspects of particle physics in other subject areas. This way, particle physics does not have to be taught as an independent topic but the main concepts are developed over time and can be integrated in the understanding of physics gradually. This may reduce the danger that students are overwhelmed with the introduction of new concepts and terminology within a short period of time.

Concluding all of that, labelling the spectrum of existing elementary particles as the SM, like it is done in figure 1, does not reflect the state of scientific knowledge. The SM has to be thought of as a theory of particle interactions. But what exactly hides behind the term interactions and how can they be described? What particle properties define the way and strength of interaction? The following subsection deals with exactly those fundamental questions.

3.2. Charges and fundamental interactions

One of the most important research goals in physics has always been to simplify the way we describe the world we live in. Simplifying in this context does not mean the reduction of mathematic complexity but the reduction of underlying core principles and assumptions that are necessary to describe various phenomena. In the history of science one can identify key moments, when some sort of unification was achieved that pushed humanities understanding of nature significantly forward in a short period of time and opened the way for “new physics”. Several of them are also addressed in scholar education. One example is the unification of the laws for falling bodies (Galilei) and the description of celestial objects (Kepler) by Isaac Newton in his theory of gravity. Also the unification of electric and magnetic phenomena by Maxwell and the connection of space and time by Einstein are examples of this type of milestones in the history of science.

Concerning the degree of unification, the SM is the best theory available to physicists so far. Besides gravitational effects, which are described through the theory of general relativity, all observed elementary processes can be described by the SM. Since our macroscopic world is just a low energy limit of this quantum world, all known non-gravitational phenomena can eventually be ascribed to the three so-called fundamental interactions of the SM. According to this, the SM just continues the combination of models and unification of theories that every scientifically interested person should get the chance to know and experience. This is why we see the discussion of the SM as an important step in scientific education that can easily be done at school when the inclusion of mathematics is kept as low as possible, which is the case in this developed approach. In the following it will be shown, how the fundamental interactions of the SM can be described in similar ways based on students’ prior knowledge in classical physics.

The fundamental interactions of the SM are the electromagnetic, the strong and the weak interactions. The strong interaction, for example, is responsible for the formation of nucleons out of quarks and the stability of nuclei, and therefore it can be introduced during the discussion of nuclear physics. The weak interaction is a bit harder accessible, since it mainly shows up in particle transformations like the beta transformation. There are different argumentations for its introduction, which will not be demonstrated here but can be found in [2] or in English in [8].

The electromagnetic interaction is well known to high school students and the law that describes the electric force is known as the Coulomb law:

\[ F_c = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q_1 \cdot Q_2}{r^2} \]  

(1)

Here \(Q_1\) and \(Q_2\) are the respective electric charges of the interacting particles or objects and \(r\) is the distance between them.

Figure 2 shows a comparison of the attractive potential energies of two particles as a result of the electromagnetic, strong and weak interaction at very small distances (electromagnetic and weak: electron and positron, strong: quark and anti-quark).
Figure 2. Potentials of the fundamental interactions.

At this scale the three curves qualitatively look quite similar. The smaller the scale gets, the more similar the r-dependency of the potentials becomes, leading to the idea to describe the strong and weak interaction in a similar way as the electromagnetic interaction while keeping in mind, that there must be some mechanisms that make them act more and more differently as the distance of the particles increases.

To make the interactions better comparable we write the Coulomb law (and also the electrostatic potential) in a different way than in (1). By introducing the electric charge number $Z$, the electric charge $Q$ can be written as the product of this charge number and the elementary charge $e$.

$$ Q = Z \cdot e \quad (2) $$

This idea is not new since the same is done in nuclear physics for the atomic number or proton number. With the introduction of the electromagnetic coupling parameter $\alpha_{em}$ (also known as the fine-structure constant) given by

$$ \alpha_{em} = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \quad (3) $$

the Coulomb law (1) reads as follows:

$$ F_C = \hbar \cdot c \cdot \alpha_{em} \cdot \frac{Z_1 \cdot Z_2}{r^2} \quad (4) $$

Here $\hbar$ is the reduced Planck constant and $c$ the speed of light in vacuum.

We see that (besides constants) the Coulomb force only depends on the electromagnetic coupling parameter and the electric charge numbers of the interacting particles, where the coupling parameter can be considered a property of the electromagnetic interaction itself and the charge numbers as properties of the particles. To describe the weak and strong interaction in the same way as the electromagnetic interaction, similar quantities must exist for them. Analogous to the electric charge number there is a weak charge number and a strong or also color charge vector. These particle properties have to be introduced to explain which particles participate in which interaction. Quarks participate in all of them since they have all respective charges. Neutrinos, on the other hand, only take part in the weak interaction, since they only have a weak charge number. The force laws for the weak (5) and the strong (6) interaction at very short (subnuclear) distances then read in an analogous form as the Coulomb law as follows:

$$ F_w = \hbar \cdot c \cdot \alpha_w \cdot \frac{I_1 \cdot I_2}{r^2} \quad (5) $$
Here $I_2$ and $I_2^\prime$ are the weak charge numbers of the two particles, $\vec{C}_1$ and $\vec{C}_2$ are the respective color charge vectors and $\alpha_w$ and $\alpha_s$ are the coupling parameters of the weak and the strong interaction.

So, essentially it is the concept of charge that is the base for the SM and the predictive power for the interaction of particles, and this vital idea can be directly connected to the previous knowledge students have about the electric charge. At this point it should be not too surprising, that all three types of charges have similar properties. They are additive, meaning that the charge numbers and the color charge vector of a composed particle is the sum of the respective quantities of the elementary particles it is built of. Secondly, all these particle properties are quantized, so only certain discrete values exist and, which is probably most important for the discussion of particle interactions, they are all conserved quantities. The deeper reason for that is that main assumptions of the SM are so-called local gauge symmetries regarding these charges and according to Noether’s theorem for every symmetry in physics there must be a connected conservation law. Therefore, the role of charges in particle physics is as important as, for example, the role of energy and energy conservation for physics in general.

Figure 3 sums up the previous argumentation by showing the relationships of the three basic concepts within the SM and settles the framework for the whole educational approach. It can be considered the most important graphic of all our teaching material

![Figure 3. The basic concepts of the SM [2, translated].](image)

Until now, the fundamental interactions only have been discussed in context of potentials and forces. But there is a major difference concerning the term interaction in classical and particle physics. The SM is not only a quantum theory, but a quantum field theory, which means that the amount of existing particles is not time-invariant but the production and annihilation of particles is allowed. The production of particles as well as a particle transformation is, for example, relevant during beta transformations, which, as a substantial part of education in nuclear physics, is a recurrent example within our argumentation. The annihilation of matter and anti-matter has, for instance, a medical application in the positron-emission tomography.

In particle physics, the term interaction is a hypernym integrating the four different phenomena of force, particle transformation, particle production and particle annihilation. From this point of view, one has to be very careful not to mix up the terms interaction and force. In literature, the terms force and interaction are used synonymously. Often statements like the following can be found: “The weak force [...] manifests itself in nuclear $\beta$-decay” [10] or “this [strong] force is the fundamental strong interaction” [11]. Statements like these are very problematic, because the understanding of the concept of force in a Newtonian way is established at school with a lot of effort and this concept is absolutely not compatible with the processes of particle transformation, production or annihilation. So to distinguish between the
terms interaction and force is highly important and the term force should only be used when actually a repulsive or attractive force is meant.

3.3. Reaches of the fundamental interactions and messenger particles

By all the conceptual similarities, there obviously have to be differences between the three fundamental interactions of the SM. The reason why the weak and strong interaction were discovered that late is their constraint to subnuclear distances, which makes them, in contrast to electromagnetism and gravity, not directly noticeable in our macroscopic world. At school the two macroscopic interactions and their forces are described with the field line model. The laws of Newtonian gravity and electromagnetism require field lines that reach into infinity or end on other objects that underlie the same interaction. For the weak and strong interaction this obviously cannot be true since their reach (and therefore the reach of their forces) is extremely limited. The strong force suddenly gets constant at scales of around 0.2 fm leading to the so-called confinement (quarks cannot exist individually). The weak force however diminishes rapidly at even smaller distances. The attempt to draw field line pictures that visualize these $r$-dependencies unavoidably leads to pictures that are not compatible with the known rules for field lines as shown in figure 4.

![Figure 4](image)

**Figure 4.** Field lines for forces with infinite reach (a), the strong (b) and the weak force (c) [2, edited].

This cognitive conflict serves as the motivation for introducing the messenger particle model to describe particle interactions. Students are quite familiar with one of them from electrodynamics, nuclear and quantum physics. This is the photon as the quantum of the electromagnetic field and the messenger particle of the electromagnetic interaction. These messenger particles can be emitted or absorbed by matter particles that possess the respective charge of the dedicated interaction. In this course, energy and momentum can be exchanged and particle transformations are possible. The properties of these messenger particles define properties like the specific reach of that interaction. The photon can always be taken to compare these properties and the following respective consequences.

The (effective) short reach of the strong interaction and the confinement can only be understood after the strong color charge has been introduced, since it is a fact that the messenger particles of the strong interaction, namely the gluons, possess this type of charge themselves and therefore, in contrast to photons whose electric charge number is zero, interact with each other. The reason for the short reach of the weak interaction on the other hand can be found in the extremely great masses of the dedicated messenger particles, the W and Z particles (photons in comparison are massless). With this knowledge the general equations for the potential energies of the strong and the weak interaction can be discussed and interpreted, which will not be done here.

Another reason for the introduction of the messenger particle model is that neither particle transformations nor the production or annihilation of particles can be visualized with the field line model since it is only suitable for the visualization of forces. The existence of these messenger particles is, by the way, also a direct consequence of the local gauge symmetries and therefore predictable by theory.
3.4. *A glimpse on Feynman diagrams*

To visualize particle interactions we recommend introducing Feynman diagrams. These types of diagrams act as visual representations of certain processes but can also be translated in elaborate mathematical equations, which is not the aim during high school education. Nevertheless, Feynman diagrams offer opportunities for exercises and the deepening of concepts like charge conservation and open the way to discuss aspects of quantum physics like superposition, interference and uncertainty. Due to their intrinsic symbolism with different arrow directions for particles and anti-particles, these diagrams can also be used to deduce allowed processes from the ones that are already known and proved to be possible. For example, the K-electron-capture and a diagram for the first experimental detection of neutrinos can be directly deduced from diagrams that represent beta transformations. For the latter just rotate the Neutrino line from the side outgoing (right) to the side of the ingoing particles (left). Due to the change of the arrow direction the anti-neutrino becomes a neutrino. Actually, at first anti-neutrinos were detected in the Cowan-Reines neutrino experiment [12] but the idea is the same. Just change the diagram for the beta minus transformation to the one of the beta plus transformation.

![Figure 5. Feynman diagram for the beta minus transformation with (a) and without (b) black box [2, edited]](image)

In these diagrams anti-particles are visualized by an arrow against the direction of time, which should not be mistaken for the indication of direction of flight. In general, one should not try to interpret any directions and velocities within Feynman diagrams since this is neither useful nor possible.

The usefulness and also the difficulties in the introduction of Feynman diagrams cannot be discussed in detail here but these diagrams are an appropriate example of the spiral approach within the presented educational concept. Before knowing about messenger particles, Feynman diagrams with a black box can already be introduced to visualize selected processes and to internalize the rules concerning the line types and arrow directions. Figure 5 shows a representation of the beta minus transformation in a Feynman diagram with black box (a) and without black box (b) revealing emission of a W particle by a down-quark which thereby is converted into an up-quark (turning a neutron into a proton).

These diagrams might look complicated at first, but actually any diagram that we intend to discuss in high school can be constructed by putting together any of the four so-called fundamental vertices which can be thought of as building blocks for Feynman diagrams. These vertices are given in figure 6. These vertices represent the emission (a) and absorption (b) of a messenger particle by a matter particle and the annihilation (c) and production (d) of matter and anti-matter.

![Figure 6. Fundamental vertices of Feynman diagrams [5, edited]](image)
4. Perception of the concept and conclusion
The received feedback from high school physics teachers after the presentation of the concept during the teacher trainings has overall been very positive. After the training the participants were asked to fill out an evaluation form by expressing their agreement with given statements on a five-level Likert scale. These forms are intended to improve the trainings. Therefore, they were changed at the beginning of 2018 since also the trainings have been improved with regard to the received feedback and the gained experience. This is why data from 2017 and 2018 are treated separately. A total of 245 teachers filled out these forms in 2017 and 2018. 64 % of them stated that the topic has high or rather high relevance for their work at school and 25% stated that this is partly true. In 2017 68 % agreed or rather agreed with the statement, that they feel capable of teaching particle physics after the training and 21% agreed partly. 95% of the participants in 2018 would recommend the training to colleagues with the rest being undecided.

These numbers and the received individual oral and written feedback on open questions indicate that the chosen approach to teaching the SM can be viable in high school education. Whether this is true in practice will hopefully be shown within the next years, when the participants will have implemented the ideas into their teaching and direct feedback out of the classroom can be gained.

The numbers of applicants for the trainings also show that there is a high demand for these types of trainings. Apart from few exceptions the capacity of the trainings was exceeded. For 2019 trainings are planned to a similar.

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