Chapter 3
Fostering Students' Creativity and Critical Thinking in Science Education

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Abstract What does it mean to redesign teaching and learning within existing science curricula (and learning objectives) so that students have more space and appropriate tasks to develop their creative and critical thinking skills? The chapter begins by describing the development of a portfolio of rubrics on creativity and critical thinking, including a conceptual rubric on science tested in primary and secondary education in 11 countries. Teachers in school networks adopted teaching and learning strategies aligned to the development of creativity and critical thinking, to these OECD rubrics. Examples of lesson plans and pedagogies that were developed are given, and some key challenges for teachers and learners are reflected on.

Keywords Creativity · Critical thinking · Science education · Innovation in education · Rubrics · Lesson plans

3.1 Introduction

What does it mean to redesign teaching and learning within existing science curricula (and learning objectives) so that students have more time and appropriate tasks to develop their creative and critical thinking skills?

The first difficulty to overcome is to operationalise the concepts of creativity and critical thinking so that each would be tangible and visible for science teachers. What do creativity and critical thinking mean in science education? What do these mean when students are not yet experts in their domain? To answer these questions, the OECD developed a portfolio of rubrics on creativity and critical thinking through

The analyses given and the opinions expressed in this chapter are those of the author and do not necessarily reflect the views of the OECD and of its members.

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A. Berry et al. (eds.), *Education in the 21st Century*,
https://doi.org/10.1007/978-3-030-85300-6_3

a quick prototyping model, including a conceptual rubric on science that was tested in primary and secondary education in 11 countries between 2015 and 2019 (Vincent-Lancrin et al., 2019).

This chapter will show how teaching and learning strategies aligned to the development of creativity and critical thinking – and to those rubrics – could be used in science education. The first section will present the rubrics and how they related to theories of creativity and critical thinking in general. The second section will present two examples of lesson plans and pedagogies that were developed during the OECD project to foster and assess creativity and critical thinking in education. Beyond the above-mentioned rubrics, these lesson plans illustrate how the development of creativity and critical thinking skills can look in practice in a science unit. The chapter will also reflect on some key challenges for teachers and learners to make the development of creative and critical thinking skills possible. It will conclude by highlighting the importance of integrating similar approaches in other school subjects so that students experience enough opportunities to develop those skills.

3.2 How to Support Creativity and Critical Thinking in Science Education: Concepts and Rubrics

Most contemporary education systems include creativity and critical thinking as part of their list of key skills students should acquire in their schooling. Most curricula in OECD countries do include in one form or another critical thinking and creativity as expected learning outcomes. Their importance in education and higher education has become consensual worldwide (Fullan, Quinn & McEachen, 2018; Newton & Newton, 2014; Lucas & Spencer, 2017). The role of education in the development of critical thinking is also increasingly acknowledged within many countries, where a majority of the population believe that schools should help students to become "independent thinkers" rather than passive receivers of transmitted knowledge – or at least recognise the importance of such an objective (Fig. 3.1). Developing critical thinking and creativity leads to more independent thinking, which can thus be considered as a good proxy for those skills .

However, even though the importance of creativity and critical thinking is usually well accepted, it remains unclear to teachers what these terms actually mean and entail in education. In order to create a shared professional language on creativity and critical thinking in education, the OECD worked over five years with a network of schools and teachers in 11 countries (Vincent-Lancrin et al., 2019). (The countries are: Brazil, France, Hungary, India, the Netherlands, Slovak Republic, Russian Federation, Spain, Thailand, United States, United Kingdom [Wales].)

In addition to the lack of clarity on the definitions of those skills, another difficulty lies in the levels of teacher-friendliness of the language used. To this effect, a portfolio of rubrics was developed to help teachers be more informed, intentional

Answer to the question: "It is more important that schools in our country teach…"

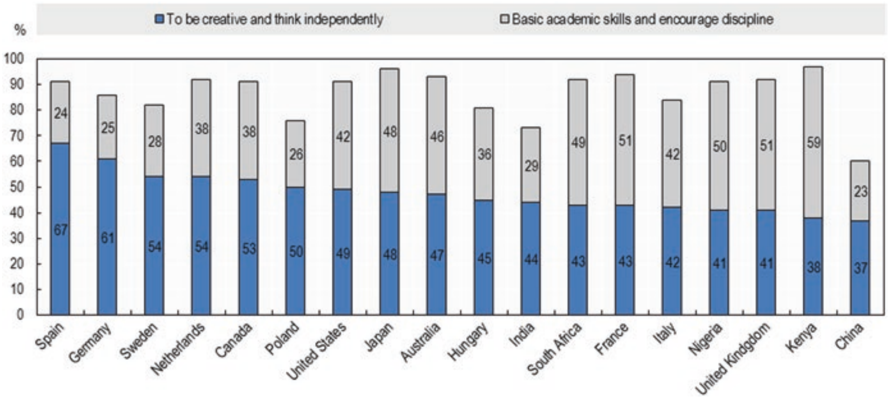

Fig. 3.1 Many societies support the fostering of creativity and critical thinking in education. (Source: Pew Research Centre, Spring 2016 Global Attitudes Survey)

and consistent in their efforts to develop their students' creativity and critical thinking. A conceptual rubric for science education is part of this portfolio.

3.2.1 Creativity and Critical Thinking

Creativity and critical thinking are two distinct but related higher-order cognitive skills. As such, both require significant mental effort and energy; both are cognitively challenging. Creativity aims to create novel, appropriate ideas and products. Critical thinking aims to carefully evaluate and judge statements, ideas and theories relative to alternative explanations or solutions so as to reach a competent, independent position – possibly for action.

The research on creativity and research on critical thinking actually do not overlap much, even though critical thinking often plays an important role in creativity, and vice versa (see Ellerton & Kelly, Chap. 2). School curricula and educational rubrics are however prone to group the two together and to talk about "creative and critical thinking". In the same spirit, Lucas and Spencer (2017) include critical thinking (as well as problem solving) under the concept of "creative thinking".

Sternberg and Lubart (1999) proposed a simple definition of creativity: "creativity is the ability to produce work that is both novel (i.e., original, unexpected) and appropriate (i.e., useful, adaptive concerning tasks constraints" (p. 3). The use of "appropriate" in this definition reminds us that creativity happens within a system or context with its established standards; it is not just about doing something new. As Dennett (2013) puts it: "Being creative is not just a matter of casting about for something novel – anybody can do that, since novelty can be found in any random juxtaposition of stuff – but of making the novelty *jump* out of some *system*, a system that has become established, for good reason" (p. 45).

Emphasising both process and output, Lubart (2000) defines creativity as "a sequence of thoughts and actions that leads to novel, adaptive production" (p. 295). What is this sequence? Creativity research has explored the cognitive processes involved in creativity. Guilford (1950) emphasised two processes leading to creativity: *divergent thinking* (generating many ideas) and *convergent thinking* (choosing and developing a good one). Torrance (1970), distinguished four aspects of the creativity process: *fluency* (having many relevant ideas), *flexibility* (having different types of relevant ideas), *originality* (having statistically novel ideas) and *elaboration* (being able to elaborate one's ideas). Most standardised tests of creativity or creative potential (e.g., Torrance, Wallach-Kogan, Guilford, Getzel-Jackson, Mednick, Runco) decompose the creative process along similar lines and focus on some of its aspects.

Critical thinking may be a step in the creative process, or may not: convergent thinking does not necessarily have to be "critical" (Runco, 2009). Critical thinking mainly aims at assessing the strength and appropriateness of a statement, theory or idea through a questioning and perspective-taking process – which may in turn result (or not) in a possibly novel statement or theory. Critical thinking need not lead to an original position to a problem: the most conventional one may be the most appropriate. However, it typically involves the examination and evaluation of different possible positions.

In education (including higher education), the theory of critical thinking has been developed by philosophers such as Ennis (1996, 2018), Facione (1990) and McPeck (1981) (see Davies & Barnett, 2015, and Hitchcock, 2018, for overviews of the literature). Hitchcock (2018) summarises most conceptions by defining critical thinking as "careful goal-directed thinking" – another version of Ennis' definition: "reasonable reflective thinking focused on deciding what to believe or do" (Ennis, 2018, p. 165). In many cases, definitions of critical thinking emphasise logical or rational thinking, that is, the ability to reason, assess arguments and evidence, and argue in a sound way to reach a relevant and appropriate solution to a problem. However, critical thinking also includes a dimension of "critique" and "perspective-taking". In addition to rational or logical thinking, critical thinking thus includes two other dimensions: the recognition of multiple perspectives (and/or the possibility of challenging a given one) and the recognition of the assumptions and limitations of any perspective, even when that perspective appears superior to all other available ones.

Many of the cognitive processes involved in creativity and critical thinking share commonalities. Both require prior knowledge in the domain of application. The sub-skills that need to be deployed for each skill involve imagining, inquiring, doing and reflecting. Creativity puts more emphasis on imagining (brainstorming, generating ideas and alternatives), while critical thinking places more emphasis on "inquiring", including its more analytical and systematic dimensions (understanding and decomposing the problem, etc.). Critical thinking is primarily inquisitive, a detective way of thinking; creative thinking is more imaginative, an artist way of thinking. However, critical thinking does involve imagining alternative theories, counterfactuals, reasons, and results in an action (making a judgment); creativity does require making judgments and decisions about the alternative ideas generated in the imaginative process, and, more fundamentally, the examination of the assumptions of existing solutions and conventions. In this sense, creativity and critical thinking can be thought of as two ends of a continuum.

Both creativity and critical thinking require a certain level of openness and curiosity. Both may lead to challenges to authority, values or accepted norms; this is what may make them both valuable, and sometimes challenging. Critical thinking requires integrity; creativity requires discipline and judgment. When education is conceived as the mere transmission of socially accepted knowledge, there is little room for either. In fact, like most other skills, creativity and critical thinking only have to be exercised at some points; even if a world in which people would be creative all the time or critical all the time was concretely possible this world would be most dysfunctional. Students also need to learn when and about what they can or should think creatively or critically. In an educational context, both creative and critical thinking necessarily pursue the deeper understanding of knowledge and solutions, and thus deeper learning. Developing creativity and critical thinking is actually a way to improve learning and achievement – whether such thinking leads to the proposing of new knowledge and solutions or not.

Even though one can describe them at the conceptual level in a domain-general way, both creativity and critical thinking in practice are mainly domain-specific: each requires knowledge about a field or context to be practiced, and usually being a strong creative or critical thinker in a particular domain does not imply any transfer of those skills to another domain. The research literature overwhelmingly emphasises the "domain-specificity" of both, even though at the conceptual level each can be described in a domain-general way.

3.2.2 Rubrics to Support Creativity and Critical Thinking in Science Teaching and Learning

There is overall a common understanding among researchers on the key dimensions of creativity and of critical thinking. However, transferring the concepts to a consistent educational application requires further translation. This is where rubrics intervene. Rubrics are a way to simplify, translate and construct social representations of what creativity and critical thinking look like in the teaching and learning process, and so create a shared understanding of what each means in the classroom, and lead to common expectations among teachers, and among teachers and students. The function of rubrics is to simplify and elaborate the complex concepts of creativity and critical thinking so that they become relevant to teachers and learners in their actual educational activities. The rubrics also allow teachers to monitor and formatively assess whether their students develop those skills. Rubrics are a metacognitive tool that helps make learning visible and tangible, and teaching intentional.

Different types of rubrics serve different purposes. “Conceptual rubrics” are those that clarify “what counts” or “what teachers and students should particularly keep in mind”, while “assessment rubrics” articulate levels of progression or proficiency involved in the acquisition of creative and critical thinking skills. Both types were developed in the OECD project from which this chapter draws, here we will focus on only the conceptual rubrics.

The development of rubrics requires balancing between simplicity and complexity. To be useful for teachers and classrooms, rubrics have to be teacher-friendly (and possibly student-friendly), and have a language that is easily understandable by teachers at different school levels. On the one hand, the descriptors of the different key ideas have to relate sufficiently to the concepts as understood by experts in creativity and critical thinking. On the other hand, the descriptors have to be simple enough to be easily understood by teachers and students, and have to relate to skills and activities that are meaningful in school settings. Ideally, one would easily memorise some of the language used in the rubric so that this becomes internalised. Using a language inspired by the “five habits of mind” rubric developed by Lucas, Claxton and Spencer (2013), and a review of other existing rubrics, the OECD rubrics that are the focus in this chapter tried to capture different dimensions of both creativity and critical thinking through four high level and easily memorable descriptors (dimensions): *imagining*, *enquiring*, *doing*, *reflecting*. Each of those active words is then associated with some more specific descriptor(s) for creativity and for critical thinking.

Two domain-general conceptual rubrics were developed: a “comprehensive” rubric and “class-friendly” rubric. Domain-specific adaptations of those rubrics were also developed, including for science. Table 3.1 shows the “comprehensive” domain-general rubric, while Table 3.2 presents the “class-friendly” rubric for creativity and critical thinking in science education.

In the case of creativity, the four dimensions in the left hand column of Table 3.1 can be elaborated as follows:

- *Inquiring*. This dimension of the creative cognitive process is close to scientific inquiry. Torrance (1966) highlights the importance of identifying problems, gaps in knowledge, missing knowledge and elements in the creative process. Because creativity cannot happen without knowledge about the field or problem investigated, looking for information, finding the problem and understanding its different possible dimensions are important aspects of the creative process. These can take different forms, depending on the problem, from feeling and empathising with people to a more objective approach of observing, describing and analysing from different possible perspectives what the issues and problems at stake are. Both curiosity and unconventional connections between different knowledge and problems matter in the creative inquiry process.
- *Imagining*. Imagination refers to the ability to see and play with ideas and things in one’s mind. This ability allows people to get free from conventional reality

Table 3.1 OECD rubric on creativity and critical thinking (domain-general, comprehensive)

	CREATIVITY (Coming up with new ideas and solutions)	CRITICAL THINKING (Questioning and evaluating new ideas and solutions)
INQUIRING	• Feel, empathise, observe, describe relevant experience, knowledge and information	• Understand context/frame and boundaries of the problem
	• Make connections to other concepts and ideas, integrate other disciplinary perspectives	• Identify and question assumptions, check accuracy of facts and interpretations, analyse gaps in knowledge
IMAGINING	• Explore, seek and generate ideas	• Identify alternative theories and opinions and compare or imagine different perspectives on the problem
	• Stretch and play with unusual, risky, or radical ideas	• Identify strengths and weaknesses of evidence, arguments, claims and beliefs
DOING	• Produce, perform, envision, prototype a product, a solution or a performance in a personally novel way	• Justify a solution or reasoning on logical, ethical or aesthetic criteria/reasoning
REFLECTING	• Reflect and assess the novelty of chosen solution and of its possible consequences	• Evaluate and acknowledge the uncertainty or limits of the endorsed solution or position
	• Reflect and assess the relevance of chosen solution and to its possible consequences	• Reflect on the possible bias of one's own perspective compared to other perspectives

Note: This rubric is intended for teachers/faculty use to identify the student skills related to creativity and to critical thinking that they have to foster in their teaching and learning, not for assessment

and to pursue novel ideas and invent new stories, anticipate the future, pursue different scenarios, envision counterfactuals, simulate consequences of different ideas and solutions, etc. In the context of creativity, imagination is about a free and playful generation of ideas, theories and assumptions, with a certain level of intentionality. This can take the form of an independent generation of multiple ideas or association of ideas, either by seeing actual or sometimes metaphorical connections (Mednick, 1962; Runco, 2009). Being able to push ideas to their limits, or to explore unconventional (or even seemingly absurd) ideas without much actual risk, is one of the cognitive processes that creativity may involve.

- *Doing*. Creativity implies the creation of something novel and appropriate, based on one's inquiry and imagination. This is typically the convergent or integrative part of the creative process. This output production can take different forms based on the domain: it can be a product, a performance, an idea, a physical or mental model, etc. It implies the selection of some of the ideas that have been imagined and inquired, and thus some level of reflection and audacious decision-making to meet the two main aspects of creativity. While products can be associated with the final stage of the creative process, the creative process can also

Table 3.2 Class friendly rubric (Science)

	CREATIVITY (Coming up with new ideas and solutions)	CRITICAL THINKING (Questioning and evaluating new ideas and solutions)
INQUIRING	• Making connections to other scientific concepts	• Identify and question assumptions and generally accepted ideas of a scientific explanation or approach to a problem
IMAGINING	• Generate and play with unusual and radical ideas when approaching or solving a scientific problem	• Consider several perspectives on a scientific problem
DOING	• Pose and propose how to solve a scientific problem in a personally novel way	• Explain both strengths and limitations of a scientific solution based on logical and possibly other criteria (practical, ethical, etc.)
REFLECTING	• Reflect on steps taken to solve a scientific problem	• Reflect on the chosen scientific approach or solution relative to possible alternatives

Note: This rubric identifies the main relevant subskills related to creativity and critical thinking that students should develop as part of their science education. It is not meant to score students or provide them with a continuum of skill progression

include some tinkering processes of trial and error, or the development of prototypes and models, and can intervene at different stages of the process.

- *Reflecting*. Finally, intentionality and reflection are key aspects of creativity. Intentionality distinguishes creativity from random novelty, and sometimes from small children's spontaneity. The level of intentionality and reflection can vary with age, but also with one's level of creative proficiency. As noted above, reflection also occurs at different stages of the creative process as one decides which ideas to select and how to move forward.

While these different aspects of creativity do not necessarily come in a definite order, or are solicited at different points in the creative process, the four can easily be related to the design thinking method, which codifies the innovation or creativity process and aims to turn it into an art (Kelley, 2001; see Kelly and Ellerton, Chap. 2). For educational purposes, the d.school at Stanford University summarised the innovation process in five steps that can be looped: empathise, define, ideate, prototype, test. Many of those processes are included in the proposed rubrics.

In the case of critical thinking, in order to have a parallelism with creativity, the underlying cognitive processes or sub-skills can be described under the rubrics' headings:

- *Inquiring*. Determining and understanding the problem at hand, including its boundaries, is a first important dimension of critical thinking's inquisitive process. Sometimes this includes wondering about why the problem is posed in a certain way, or examining whether the associated solutions or statements may be based on inaccurate facts or reasoning and identifying the knowledge gaps. This inquiry process partly concerns rational thinking (checking facts, observing, analysing the reasoning), but also includes a more "critical" dimension when it comes to identifying the possible limitations of the solution and challenging some of the underlying assumptions and interpretations, even when facts are accurate. In many cases, inquiring involves acquiring knowledge, verifying knowledge, and examining the components of the problem in detail as well as the problem as a whole.

- *Imagining*. In critical thinking, imagination plays an important role as the mental elaboration of an idea – but any thinking involves some level of imagination. At a higher level, imagining is also about identifying and reviewing alternative, competing world views, theories and assumptions, so as to consider the problem from multiple perspectives. This allows for a better identification of the strengths and weaknesses of proposed evidence, arguments and assumptions, even though this evaluation also belongs to the inquisitive process. Imagination also plays a role in thought experiments, which can be a strong component of any good thinking and also a way to make a point when experimentation is not possible (Dennett, 2013).
- *Doing*. The product of critical thinking is one's position or solution to a problem (or judgment about others' positions or solutions). This mainly implies careful inference, a balancing act between different ways of looking at the problem, and thus recognition of its (possible) complexities. As in any productive thinking, critical thinking implies the ability to argue and justify one's position rationally, according to some existing perspectives and socially recognised ways of reasoning, or possibly some new ones.
- *Reflecting*. Finally, even though one may consider one's position or way of thinking superior to some alternatives, perhaps just because it embraces a wider view or is better supported by existing evidence, critical thinking implies some self-reflective process about the perspective one endorses, its possible limitations and uncertainties, and thus a certain level of humility and openness to other competing ideas. While one does not have to embrace ancient scepticism and suspend one's judgment in all cases, this may sometimes be the most appropriate position.

The OECD rubrics for creativity and critical thinking were meant to be used by teachers working in real-life settings in different ways: (1) designing and revising lesson plans so that they would give students the opportunity to develop their creativity and critical thinking skills; (2) assessing student work and progression in the acquisition of these skills; (3) generating new aligned rubrics adapted to their local context or self-assessment tools. Field work showed that seven in ten teachers participating in the international network did on average use the OECD rubrics for those purposes. The rubrics have thus proven to be useful and well adopted by teachers in most of the countries in which the project was implemented.

3.2.3 Creativity and Critical Thinking in Science

While science education can be one of the many vehicles to develop students' creativity and critical thinking in a school context, it is noteworthy that critical thinking and creativity are also at the core of scientific practice. When practiced by expert scientists, science is about creativity and critical thinking.

Scientists usually need to have creative or original ideas to receive grants and get published in scientific journals. Scientific awards (such as the Nobel Prizes) typically celebrate advances that bring some ideas or techniques that are "new to the world" (and in this sense, creative in the full meaning of the word). One aspect of scientific practice that is usually somewhat downplayed is "imagination". It is nevertheless a key aspect of science as Nobel Prize winner and famous physicist Feynman (1963) noted:

> *Experiment is the sole judge of scientific "truth."* But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws, in the sense that it gives us hints. But also needed is imagination to create from these hints the great generalizations—to guess at the wonderful, simple, but very strange patterns beneath them all, and then to experiment to check again whether we have made the right guess. This imagining process is so difficult that there is a division of labor in physics: there are theoretical physicists who imagine, deduce, and guess at new laws, but do not experiment; and then there are experimental physicists who experiment, imagine, deduce, and guess. (p. 1)

As for critical thinking, it is in fact at the heart of scientific progress – and one of the prerequisites of science. Science's very core value is doubt, the possibility to question what authorities (including teachers and scientists) say. There is no science without a certain level of scepticism, as Feynman (1955) forcefully noted:

> The scientist has a lot of experience with ignorance and doubt and uncertainty, and this experience is of very great importance [...] We have found it of paramount importance that in order to progress we must recognize our ignorance and leave room for doubt. Scientific knowledge is a body of statements of varying degrees of certainty - some most unsure, some nearly sure, but none absolutely certain. […] Our freedom to doubt was born out of a struggle against authority in the early days of science. It was a very deep and strong struggle: permit us to question - to doubt - to not be sure. I think that it is important that we do not forget this struggle and thus perhaps lose what we have gained. Herein lies a responsibility to society. […] It is our responsibility as scientists… to teach how doubt is not to be feared but welcomed and discussed; and to demand this freedom as our duty to all coming generations. (pp. 245–247)

Teaching and learning creativity and critical thinking in science education in schools is thus one way to "think like a scientist" and understand the values of science, even if, as for the technical skills in science (that is, the mastery of content and procedural knowledge), students are not necessarily expected to be as proficient as expert scientists – not to mention the most celebrated ones.

3.3 Creativity and Critical Thinking in Action in Science Education

Depending on the subject of the lesson and the learning outcomes they want to achieve, using a conceptual rubric while designing a lesson helps teachers to build in some assignments or tasks giving students the opportunity to develop at least some of the sub-skills of creativity or critical thinking. Some lessons may aim to develop just a few sub-skills, while others could cover the full range, with an emphasis on either creativity or critical thinking (or both). Existing lessons could be modified according to the same process, just adding one opportunity to develop a sub-skill here and another there through small changes to the lesson or its pedagogical delivery.

The conceptual rubrics also represent a key element of a quality assurance method: after decomposing their lessons or entire course into steps, teachers can identify when students were given the possibility or were requested to practice some of the skills identified in the rubric. Examples of lesson plans developed during the lessons/ course can thus include a mapping of the different steps of the lesson against the sub-skills of the conceptual rubrics.

Teams working on redesigning their science education courses implemented the OECD project that is the focus of this chapter in different ways. Two "signature pedagogies" were used by some of the teams (project-based and research-based learning), while most others just designed short projects or activities or improved more traditional lesson plans.

One example of lesson plans in science education grounded in project-based learning, and included in the OECD examples of courses, is now presented to give tangible ideas of how critical thinking and creativity can be developed in science education while also teaching technical skills of science (declarative and procedural knowledge).

3.3.1 What Controls My Health?

Developed by Adler et al. (2017), "What controls my health?" is a 20-lesson course engaging students in investigations to understand the importance of both genetic and environmental factors in their risk for disease. Students start the unit by experiencing the phenomenon of Type 2 diabetes through the eyes of a peer recently diagnosed with the disease. They develop an initial model to answer the driving question of the whole project: "What caused Monique's diabetes?" The driving question is particularly relevant to the students for whom it was designed and who live in Detroit, a city which is predominantly African-American and where most students are likely to have relatives suffering from diabetes.

Throughout the unit, students learn that diabetes, like many common diseases, is caused by a combination of both genetic and environmental factors. They also investigate how lifestyle options for healthy foods and exercise help prevent or reduce Type 2 diabetes. One lesson includes several opportunities for students to construct, test, revise and share their models to explain the investigated phenomena, while performing experiments and using computer simulations. For their final assignment, students conduct an action research project, based on their scientific and technological knowledge and understanding, which aims to improve the health of their school or neighbourhood to help prevent or reduce diabetes.

A summary description of the course is now presented (a more elaborated outline is publicly available at Adler et al., 2017):

1. *Periods 1–2: Why does Monique have diabetes?* Students learn about Type 1 and Type 2 diabetes (video). They develop an initial model that explains a health phenomenon of their choice.
2. Periods 3–5*: How can we describe Monique's diabetes?* Students learn more (through reading), and share information about the cause, symptoms and treatment of both Type 1 and Type 2 diabetes. They perform a glucose tolerance test by analysing simulated blood plasma samples to determine if the person has Type 1 or Type 2 diabetes. They learn about the heart, as an example of an organ which may be affected by diabetes. They revisit the *Driving Question Board*[1] and reflect upon their learning. They revise their models and add the biological aspect of diabetes to their model.
3. Periods 6–9: *How does Monique's family affect her diabetes?* Students examine pictures of a family to identify some genetic factors of characteristics that might be inherited. They collect data on tongue rolling and arm span, and use these data to explore the population variation of the inheritance patterns of single and multi-factorial genes. They use beads to simulate the inheritance of risk factors for diabetes. They identify the risk of diabetes in offspring based on the number and type of risk factors inherited during the simulation. They revisit the *Driving Question Board* and reflect upon their learning. They revise their models and add the effect of genetic factors on Monique's diabetes.
4. Periods 10–12: *How does where Monique lives and what she does affect her diabetes?* Students study the influence of environment on living organisms through plant growth.
5. Periods 13–16: *How do Monique's characteristics and environment affect her diabetes?* Through simulation, students consider how genetics and environment affect the health of sand rats.
6. Periods 17–18: *What can Monique do to make her environment healthier?* Students study the role of nutrition.
7. Periods 19–20: *Community action projects: How can we work together to make our environment healthier?* Students develop and choose their inquiry question, design and develop their research tools, then plan and carry out their investigations. They analyse the data and draw conclusions, share their findings with their

[1] Many project-based science units/ courses initially develop "Driving Questions" to contextualise the unit and give learners opportunities to connect the unit to their own experiences and prior ideas.

peers and broader community, suggest solutions and potential actions based on their findings.

This sequence is a good example of how teachers could allow their students to learn about science technical skills while giving them opportunities to also develop their creativity and critical thinking (as well as some social and behavioural skills). In terms of technical skills, that is, the mastery of content and procedural scientific knowledge, students clearly learn about: diabetes; the heart as an organ; the growth of plants; genetics, the influence of environmental factors; nutrition; the multiple drivers of health; making tests and experiments, including through computer simulation, and interpreting them.

The main focus of the "What controls my health?" course is actually critical thinking as students: identify and question their assumptions or accepted ideas about diabetes and its causes (steps 1 and 7 above); consider several perspectives on the problem at hand (steps 3 to 6); explain both the strengths and limitations of their scientific solution (steps 6 and 7); and consistently reflect on the chosen scientific approaches that they consider relative to possible alternatives (steps 2, 3, 4 and 7).

The lessons also allow students to develop some creativity skills as they: are induced to make connections to other scientific concepts or ideas throughout the project and to use remote examples to better understand (heart, plants) (steps 2 and 5); generate and play with unusual ideas as they revisit the questions of the Driving Question Board and have to generate their own solution (steps 1, 4, 7); propose how to solve a scientific problem in a personally novel way (steps 1 and 7); and reflect on those steps at the end of the process (step 7).

3.3.2 Evaporative Cooling

Another 10-lesson science (chemistry) unit was developed as part of a US-Finland project on problem-based learning in science, showing how to craft optimal learning moments in science learning environments (Schneider et al., 2020). The unit was also contributed to the OECD bank of pedagogical resources and is called "Evaporative cooling" (Paddock et al., 2019). It engages students in investigating the following driving question: "when I am sitting by the pool, why do I feel colder when I am wet than when I am dry?"

Students learn about intermolecular forces and energy transfer between molecules during phase changes of matter. Students start by experiencing the phenomenon of evaporation and cooling of different liquids. Later activities include experiments to measure temperature and mass changes when liquids evaporate, and, using several computer-based simulations, to explore energy transfer, forces, and interactions between molecules in different phases. Throughout, and under the guidance and with the scaffolding of their teacher, students continuously build, use, evaluate, and revise their own computational and hand-drawn models to answer the driving question.

A summary description of the course is now presented (a more elaborated outline is publicly available at Paddock et al., 2019):

1. Lesson 1: *Why does having wet skin makes you feel cooler?* Students are introduced to the Driving Question, and construct and draw their initial model of the phenomenon in pairs so that they access their prior knowledge about this phenomenon. The purpose for the teacher is for formative assessment to inform planning for lesson 2. Student pairs explain their model to another pair in turns so that they can share ideas and begin working toward some consensus in understanding.
2. Lesson 2: *Does evaporation depend on coverage?* Students go to two stations that are designed to test the rate of evaporation of acetone, water, and ethanol and the temperature change during the process. Students observe temperature change across time while the liquid is covered and while uncovered. Students observe mass change across time (covered and uncovered), collect data and graph these. Following the activity, students answer questions to guide their noticing of patterns.
3. Lessons 3–4: *Why does having wet skin makes you feel cooler?* (a specific return to the driving question) Students review their drawn models from lesson 1 and learn how to use a new modelling tool, SageModeler (freely available at https://learn.concord.org/building-models). They create an initial model of their experimental results using the modelling tool. Students use a computer simulation to compare properties of the states of matter. Properties include: spacing of molecules (which connects with potential energy) and kinetic energy.
4. Lesson 5: *How does thermal energy work?* Students learn that thermal energy can be transferred during phase changes. They develop a model to show how a system gains or loses thermal energy.
5. Lesson 6: *Why does having wet skin makes you feel cooler?* (a further deliberate return to the driving question) Students reflect on their drawn models. They review the learning from Lesson 5 and incorporate ideas from the lesson into their SageModeler model, and share their models to receive feedback.
6. Lessons 7–8: *Do matter viscosity and intermolecular forces play a role?* Students compare viscosity of water to acetone by observing how each chemical spreads on two different surfaces (a coin and wax paper). They investigate how the strength of the intermolecular forces in a substance effect the state of matter of a substance at a certain temperature using a computer simulation.
7. Lessons 9–10: *Why does having wet skin makes you feel cooler?* (a final return to the driving question) Students revisit their model, and, in pairs again, create a final draft of the model and evaluate this using a provided rubric. Students assess their peers' models with the rubric, and make a final revision of their own model. They present their final models and explanations to the whole class and may take a unit test. Students then perform a final assessment of the unit to reflect on what has been learned.

Here, again, there are clear technical skills to be acquired, both in terms of scientific content and procedural knowledge. In terms of content knowledge, students learn about the structure of matter, the behaviour of particles, intermolecular forces, the position and arrangement of atoms, and about relationships between molecular motion, the position of molecules, and kinetic and potential energy. The model they build and revise seeks to identify a pattern between the structure of particles and the behaviour (evaporation and temperature) of particles. In terms of procedural knowledge, students learn to model a phenomenon, to experiment, to analyse data, and to revise their model.

Although the sequence of lessons is essentially science (chemistry), it also gives students more opportunities to develop their creativity - and this more than their critical thinking. Or, to put it another way, the sequence does not dwell on identifying and questioning assumptions and generally accepted ideas of a scientific explanation or approach to a problem. The lesson does not offer students as many different perspectives as the previous example sequence ("What controls my health?"), as that was organised to show how different branches of science and technology explain different interacting parts of the puzzle. Nevertheless, "evaporative cooling" does seek to help students understand that *several* aspects of matter have to be factored in to understand and explain the phenomenon.

Students exercise their scientific creativity by repeatedly imagining how the phenomenon under study can be explained, generating and playing with different ideas that are unusual and new to them, making connections with their life but also with other knowledge they have. They are given opportunities to put forward an explanation of this scientific problem in a personally novel way at different stages of the unit (lessons 3, 5 and 8). They have to imagine from the outset how the phenomenon could be explained, making connections with their own and new experiences of evaporation, and as they look for and are given new information and knowledge, they continue to play with new ideas and imagine new solutions that they revise throughout the unit. Whether they have room to play with unusual or radical ideas depends on the teacher, who could very well encourage them to go in that direction to possibly prove them wrong or help them understand what a scientific (falsifiable) statement looks like.

In the Evaporative cooling lessons students practice some of their critical thinking skills by considering several perspectives on the driving question, gradually enriching and adding new concepts within the theoretical frame in which they operate. They have considerable room throughout the lessons to reflect individually and collectively on the strengths and limitations of the successive models they elaborate, identifying gaps and looking for alternative models.

The lessons shows that, even when a unit is framed around one main "theory" or "knowledge" to learn, there is room for students to have some level of agency, to imagine possible solutions, inquire about them, craft experiments and models to test their ideas, and reflect on them.

3.3.3 Design Criteria for Good Lessons

While the conceptual rubrics presented above can support teachers to review their curriculum units and plan lessons that give students opportunities to develop the sub-skills identified by the rubrics, they do not provide guidance on all key dimensions of the pedagogical work. In fact, while creativity and critical thinking can be nurtured in any domain, within and outside of science (or other apsects of STEM), these do require giving students certain types of tasks and problems. A set of "design criteria" was thus developed by Vincent-Lancrin et al. (2019) to support teachers further, building on learning science principles, including motivation, cognitive activation, self-regulation and opportunities for formative assessment (see Table 3.3). These design criteria for good lesson plans represent another set of

Table 3.3 Design criteria for activities that foster creativity or critical thinking skills

A pedagogical activity aligned with the OECD rubric on creativity and critical thinking should:	Comments
1. Create students' need/interest to learn	• Usually implies starting with a big question or an unusual activity. • May imply coming back to these questions several times during the activity.
2. Be challenging	• Often, the lack of student engagement comes from learning goals or activities that lack challenge. The tasks should be challenging enough, though not too difficult given the students' level.
3. Develop clear technical knowledge in one domain or more	• The activity should include the acquisition and practice of both content and procedural knowledge (technical knowledge).
4. Include the development of a product	• A;product (a paper, a presentation, a performance, a model, etc.) makes the learning visible and tangible. • Teachers and students should also be attentive to and possibly document the learning process.
5. Have students co-design part of the product/solution or problem	• Products should thus in principle not look all alike.
6. Deal with problems that can be looked at from different perspectives	• Problems should have several possible solutions. • Several techniques may be used to solve them.
7. Leave room for the unexpected	• Teachers and students do not have to know all the answers. • The most commonly adopted techniques/solutions may have to be taught and learnt, but there should be room for exploring or discussing unexpected answers
8. Include space and time for students to reflect and give/receive feedback	

Source: Vincent-Lancrin et al. (2019)

quality checks and new perspectives on how to approach pedagogical redesign to foster students' creativity and critical thinking.

The "design criteria" highlight that tasks to develop and then demonstrate creativity and critical thinking skills in education share some general features: they seek to engage students, they may have a deliberately open nature, and they encourage students to explore multiple solutions to problems within parameters and constraints that clarify goals yet remain relatively flexible to allow students to address them with a certain level of agency.

The successful teaching of creativity and critical thinking also hinges critically on teachers' attitude and in their ability to create learning environments where students feel safe to take risks in their thinking and expressions. This in turn presupposes a positive attitude towards mistakes and learner empowerment. A positive attitude among teachers towards student "mistakes" or "failure" can take the form of using these to trigger reflection about opportunities for learning, thus helping students to see misunderstandings and other matters too often labelled 'failures' as a chance for improvement (see Mansfield & Gunstone, Chap. 9). Choosing questions and tasks that teachers themselves cannot resolve can make it clear to students that the thinking process behind a problem can be as important as its answer. This is typically the role of the Driving Question Board in project-based learning (Schneider et al., 2020), something that demands a positive teacher attitude towards students' questions, and also students' explanations.

3.4 Concluding Remarks

To foster their students' creative and critical thinking skills in science education, teachers have to be intentional – and thus clear about what creativity and critical thinking mean in an educational setting, what subskills they should have their students practice, and what they should observe and monitor in the classroom. This clarity could typically be provided by the use of rubrics on creativity and critical thinking, both to create a more accessible and better understanding of what creativity and critical thinking entail and to ensure that students have opportunities to practice these higher order skills during their class work.

Exemplars of lesson plans or curriculum units should typically supplement those rubrics and illustrate how to equip students with creativity and critical thinking skills while teaching and learning traditional science education subjects. It is noteworthy that resources such as rubrics and examples of lesson plans are just a second-best but a much cheaper and much more widely available option than direct professional development of teachers can ever be.

While science and STEM education can provide tasks that would allow students to develop both their critical thinking and their creativity, the consistent acquisition of creative and critical thinking skills must be reinforced by other disciplines as well. There are two main reasons for this. The first is time. It takes practice to develop any skill, and it is possible that science lessons in school cannot provide enough occasions (hours) for students to practice the creativity and critical thinking skills that have been highlighted in this chapter. Significant reinforcement and development of those skills implies that they are experienced in multiple subject areas. A second fundamental reason lies in the domain-specificity of creativity and of critical thinking. Even though creativity and critical thinking can be discussed in a general way at the conceptual level, as if the domain of their application did not matter, in practice the fact that each requires knowledge and some level of expertise in a particular field means that they have to be practiced over and over in different fields. If they were domain-general, one could teach them in special creativity or critical thinking classes, or, for example, one could have the visual arts teacher be in charge of creativity, and the science or philosophy teacher be in charge of critical thinking.

But this is not the case. Creativity and critical thinking need to become a key objective of all subjects taught in schools, something that is reflected in the general perspectives across all subject areas in many Twenty-first Century school curricula. These general curriculum perspectives are commonly intended to allow students to develop some habits of mind, but the realisation of such intentions does require a mainstreaming of those learning objectives in all subject areas of education. While science teachers might feel that they are somewhat in charge of critical thinking, as science often challenges common wisdom, they could still emphasise more the remaining uncertainty of scientific "truths" (Rennie, 2020), even though the methods through which such "truths" are established are robust. Even more so, teachers should keep in mind that science requires creativity and imagination, as what may currently appear as the most obvious and conventional scientific statement was initially created by a very imaginative scientist.

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