



Promoting Curiosity?

Possibilities and Pitfalls in Science Education

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Abstract

Curiosity is a wonder of the human mind. It goes to the heart of modernity, as a driving force for learning, novel insights, and innovation, both for individuals and communities. In societies dependent on science and development, finding out what promotes or hampers curiosity and wonder in school curricula and science education is accordingly essential. In this conceptual article, I suggest a framework for curiosity-based science education and I explore options for its wellbeing and development during preschool, preadolescence, and adolescence. In preschool, curiosity and wonder are triggered by perceptive beauty rather than by facts, and a method emphasizing maximism as a complementary factor in preschool science education is proposed. In prepuberty, curiosity is encouraged by exploring the diversity of the world. Facts and clear-cut knowledge constitute a firm foundation for scientific thinking. In high school, curiosity is ignited by means of a better balance between models and phenomenology. Criticism has arisen over the one-sided use of models in high school science education, which limits scientific thinking to frameworks defined by the actual model. Possible solutions to maintain students' curiosity and ideas to improve the balance between phenomenology and models are discussed.

Keywords Curiosity · Wondering · Science education · Maximism · Models

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Omnia mirari etiam tritissima
Carl von Linné

1 Introduction

Curiosity is a wonder of the human mind. It goes to the heart of modernity, and any civilization dependent on development and welfare rest on its vitality. Carl von Linné's famous maxim *Omnia mirari etiam tritissima* ("Find wonder in everything, even the most commonplace") decorates the Swedish bank notes and illustrates the intimate connection between curiosity, science, societal affluence, and welfare. To identify what promotes or hampers curiosity should accordingly be of primary relevance for science education and society.

The term "curiosity," however, encompasses different modes: a new hobby, the puzzling feeling when facing a peculiar problem, gossip of a societal but harmless scandal, or the excitement felt while reading a novel. Curiosity is observed among all vertebrates (Lindholm 2015). In human cultures, it circumscribes the episodic hunger for novel information, which calms when the answer is found: *What are the neighbors doing? What's in that box? What time is it? Did Princess Diana have a lover?* This rather superficial kind of curiosity is sometimes referred to as diversive curiosity (Berlyne 1954; Litman and Spielberger 2003; Leslie 2014; for a recent review, see Clark 2017).

Wonder, on the other hand, reflects the experience of naked existence beyond words, and rather addresses the framework of our knowledge (Dawkins 1998; Opdal 2001; Egan et al. 2014). One does not wonder about what time it is, but what time *is*, just as one does not wonder how old somebody is or if Princess Diana had a lover, but what aging actually *is*, and who Princess Diana *was*. Wondering is easily ignited by beauty (Hadzigeorgiou 2005; Hadzigeorgiou 2014), in art, music, bird song, flowers, or sunsets. Looking into the alien underwater from an old jetty invokes both curiosity (*Is a pike hiding under that shady log?*) and wondering (*How is this strange world possible, after all?*). Wonder touches the experience of naked being, while curiosity is more in the realm of rational exploration. Moreover, wonder has an esthetic dimension, which is less so for curiosity (Hadzigeorgiou 2012).

Between these two, there is the enduring demand for knowledge for its own sake, where curiosity is not satisfied, but fueled by new information. This deep *epistemic* curiosity (Kang et al. 2009; Leslie 2014) is the one appreciated in modernity. It emerged gradually over the course of time following Europe's Renaissance and came to fruition in the Enlightenment. It is nourished by wonder, but combines this with rational analysis and may therefore be thought of as a meeting place for diversive curiosity and wonder.

Deep epistemic curiosity is a necessity of modernity and a driving force for science, innovation, and wealth. It may even become existential, as illustrated by the case of Doctor Faustus, who sold his soul to the devil for ultimate knowledge. Epistemic curiosity rests on the belief that knowledge not only helps to solve practical problems but also satisfies our big questions too—who we are, what is meaning, and where we all go (Eaman 1994; Huff 2011; Ball 2012). It does not cease, but is nourished by new knowledge and hence widens the cognitive horizons in ever new directions. Knowledge itself begins to fuel curiosity, which penetrates ever deeper into larger questions in successive loops.

Somewhat unexpectedly, throughout history, curiosity has not always been considered a virtue, as exemplified by the myth of Pandora or the expulsion from Paradise. In fact, most cultures have rejected curiosity as a human virtue, and human welfare was rather a matter of tradition, ancient Gods, and old men. The Greeks calculated both the size, shape, and circuit of the earth, without invoking any longing for the unknown. Odysseus' voyage was not driven by curiosity, but by

jealous gods. Even today, curiosity is evaluated differently across cultures (LeVine 1970; LeVine et al. 1994; Harris 2012). Western middle-class children start asking questions at the age of 2 and 3, which is generally appreciated by their parents who easily participate in such dialogs (Chouinard 2007). In contrast, similar studies from non-western cultures (Nepal, Kenya, Belize, and Samoa) have revealed that questioning was significantly less, and hardly any questions were raised to parents (Gauvain et al. 2013). The authors noted that parents take for granted that children are obedient and respectful in these more traditionally oriented communities.

Deep, knowledge-driven curiosity must be considered a cultural trait, and not an inherent and genetically driven feature. For a society dependent on innovation and growth, the crucial question is *how pedagogy and education may nurture curiosity throughout childhood, and how to avoid checks and pitfalls*. Indeed, several studies praise the value of curiosity for learning and knowledge (Zuss 2012; Richards et al. 2013). Despite being recognized as mandatory for scientific development, however, ideas on how pedagogy may promote or hamper curiosity are nearly absent (Zion and Sadeh 2007; Egan et al. 2014; Clark 2017; Gilbert and Byers 2017). Reports on science education elaborately assess how preschool children demonstrate cognitive readiness for science, but do not consider or discuss possible long-term mechanisms which could hamper or promote deep curiosity and the persistent joy of learning (National Research Council 2007, 2012).

2 Historical Background: the Maturation of the Scientific Habit

In this article, I discuss educational practices which could favor or counteract wonder and curiosity from early childhood to adolescence, and I propose a framework for curiosity-based science education. The ideas emerged gradually during a career first comprising two decades as a science teacher, followed by two decades as a scientist. Some readers may recognize influences from pedagogy-philosophical thinkers such as Nikolai Grundtvig (1783–1872), Rudolf Steiner (1861–1925), and John Dewey (1859–1952), all of whom advocated dialog- and inquiry-based methods in science education (Dewey 1902, 1910; Grundtvig 1904; Steiner 2004). Dewey's ideas of pragmatism have been particularly inspiring, and his refutation of abstract meta-theories comes close to the phenomenological approach to child understanding advocated here. Dewey's concern was that education in science could invoke the view of science as a quantifiable amount of facts, terms and definitions, which alone hardly reveals the true process of scientific thinking. The problem of problems in science education is, according to Dewey, how to "mature the scientific habit":

The future of our civilization depends upon the widening spread and deepening hold of the scientific habit of mind; and the problem of problems in our education is therefore to discover how to mature and make effective this scientific habit. (...). Actively to participate in the making of knowledge is the highest prerogative of man and the only warrant of his freedom. When our schools truly become laboratories of knowledge-making, not mills fitted out with information-hoppers, there will no longer be need to discuss the place of science in education (Dewey 1910, p. 127).

More recently, these ideas have been replenished by the phenomenological approach of Martin Wagenschein, Martinus Langeveld, and Max van Manen, who aim to understand the child as it appears, rather than focusing on interpretations and meta-theories of child psychology. As teachers, we interact and respond to the children and students as they perform, and our educational intentions depart from there: "To come to an understanding of what is good for the child, what is educationally desirable, we must first be able to listen to the child in a manner

that respects the child's subjectivity — the way the child experiences and perceives things.” (Van Manen and Adams 2014, p. 608).

The goal of the present article is to explore how Dewey's “maturing of the scientific habit” can be systematically developed and promoted throughout childhood and adolescence. For the sake of simplicity, the discussion is limited to the ages of 3–5 years old (preschool), 10–12 years old (prepuberty), and 15–17 years old (high school). I argue for the value of wondering in preschool, increasingly emphasizing diversive curiosity in prepuberty, and finally the fusion of the two elements to deep epistemic curiosity in high school science education.

3 The *Why* or the *What?* Curiosity and Wonder in the Preschool

Research has revealed that children can be involved in science subjects and causal analysis earlier than commonly assumed (National Research Council 2007). But to recognize what is possible is by no means to say that it is desirable in the long run. Understanding the psychology of preschool curiosity and wonder, and how it relates to learning and the joy of knowledge later in life history, could be more challenging than commonly thought.

Children are often full of questions—*Why is it raining? What do the birds sing about? Where is the sun at night? What is water?* Science explores causal relationships and gives answers to *why* something is as it is. Science teachers are accordingly more familiar with the question of “why it is,” than with questions of “what it is.” And “what it is” emerges from a different corner of the mind. It is rather triggered by perceptions of the mere being of something. The “what it is” is not primarily a search for causal explanations. Wondering and curiosity accordingly reflect somewhat different modes of questioning and stimulate exploratory joy from different positions. Curiosity remains in the space of terms, concepts, and causality. Wonder emerges from a wordless experience of something's existence. And while wonder is more ignited by perception, curiosity is more ignited by reflection.

Preschool children tend to wonder about literally everything—earthworms, a crackling sound of chocolate paper, rainbows, pine needles on mud puddles, or the feeling of a breadcrumb under the fingertips—all impressions which vividly invoke “what it is” experiences (Wagenschein and Berg 1980; Langeveld 1984; van Manen 1990). A preschool teacher recounts how a girl came up to her during a walk with a ladybug in her hand. The teacher started to explain how it lives, what it eats, how it reproduces, and so on—typically leading the attention into “why it is” questions and causal relationships. But the girl kept her attention on the ladybug and did not seem to listen. Then, she quietly interrupted: “It lives in my hand!” The girl was not out for knowledge about the ladybug, but dwelled on the staggering fact of its mere existence. She was more into the wondering of “what it is” than the causal “why it is.”

Every autumn, children gather under horse chestnuts trees amazed by the conkers—gleaming nuts sliding so smoothly through the fingers, with their mild scent and luminous brown luster. The feeling is aimless and lacks any goal, but children love them for their own sake. For the same reason, toddlers fill their pockets with strange things which for adults seem meaningless—stones, sticks, corks, and cones. Preschool children unfold strongly in the realm of the senses, where everything is tuned by beauty and a tint of wonder (Abram 1996; Hadzigeorgiou 2005). Milne (2010, p. 105) emphasized the esthetic experience as a key interconnecting element that links the child “with the phenomena that will promote a sense of wonder leading to a desire for understanding and explanation of the phenomena.” And

Hadzigeorgiou and Schulz (2014), while pointing to Darwin, Faraday, and von Humbolt, emphasized that their ideas of beauty were implicit in their experience of wonder. Children are equally attracted both to beautiful marbles and, what are to adults, useless scraps.

The wondering experience of the Other (Levinas 2006), which among adults remains primarily directed towards humans, during early childhood includes literally everything. Preschool children inhabit a world of subjects (de Haan and Nelson 1999; Farroni et al. 2002), where “what it is” and “who it is” are intertwined, which leads them to animate objects. The girl’s wondering over a ladybug was ignited by the feeling of a “somebody.” Inhabiting such an animated world makes preschool children easily believe that the sun gets tired in the evening, that snails play jazz with grasshoppers, or that rubber boots enjoy stepping in mud puddles. This imaginative capacity facilitates friendship with the world and makes Winnie the Pooh, Alice in Wonderland, and folk tales so accessible.

Science education at the preschool age needs to take into account this view of natural objects as subjects and potential friends. More specifically, this means maintaining a balance between causal and ontological thinking, between the “why it is” and the “what it is,” and to leave space for dwelling in the state of wondering, and not interfering too soon by means of causal, scientific knowledge and explanations. Somewhat paradoxically, an obstacle for fruitful science education in preschool could precisely be a biased focus on causal relationships and on the “why it is.” Causal relationships are rarely obvious, but dwell behind veils of bewildering perceptions. Tracking causal relations accordingly requires reductionism, the ability to turn the attention into underlying causal reasons for something. This tendency to reduce the given, however, which later constitutes a core necessity, potentially counteracts the wondering in preschool children.

Reductionism is indeed mandatory for any science and calls for experiments to demonstrate models and ascertain causal relationships. No science is possible without reductionism. But an unintended side effect during preschool age could be the erosion of wonder. The reason is that reductionism delivers causal explanations for the child’s wondering, which removes the focus from the perception, which triggered wondering in the first place. The perceptual experience of beauty could be muted at an age where instead it should gain support.

Many scientists will remember experiencing wonder and beauty in their own childhood, which in retrospect generated reflections and gradually matured to deep curiosity and joy of knowledge. Ask a geologist what she filled her pockets with during childhood or a biologist at what age he got familiar with bird songs. Carl von Linné revealed how the beauty of flowers completely overwhelmed him as child. Charles Darwin’s passion for beetles was so strong that his father seriously doubted his mental health, and his *On the Origin of Species* ends in praise of beauty (“endless forms most beautiful...”). Einstein’s interest in physics was triggered as he, when he was five years old, got a compass which deeply fascinated him with its intriguing stable needle.

The wonder of preschoolers is not nourished by theories and models but by perceptions and senses (Lim 2004; Milne 2010). It even invades into apparent “why it is” questioning, as when toddlers ask: *Why is that bird singing? Why is the sun going down?* Such questioning is not necessarily about causal relationships, as it would be for adults (Harris 2012; Schinkel 2017). *Why does it rain?* is indeed not a call for lessons in meteorology, but rather a wondering expression of “*How is this phenomenon possible, after all?*”

In fact, the latent mismatch between the wondering preschool child and causal explanations could make one-sided scientific approaches a serious obstacle for the future joy of knowledge, if not balanced with the corresponding awareness of “what it is” questions. The reason is that

our causal explanations are so powerful that they easily override the naïve and less verbal wondering that triggered the perception. Rainbows, bird songs, or earthworms, which all are potential lifelong friends for preschool children, could turn out to be less important than their underlying causal mechanisms.

The daily explorative life of preschool children obviously needs theoretical, emotional, and practical guidance and fact-based knowledge, as well. Learning along a broad scale of didactics is indeed mandatory in any preschool, in order to stimulate children's natural curiosity, though primarily emerging from their own practical experiences. To stimulate wondering would call for a different approach, however, due to its non-verbal nature. It needs more indirect support, such as through esthetic experiences and art (Burton et al. 1999; Milne 2010).

Moreover, wonder may be reinforced by means of a certain maximizing way of storytelling and concept introductions, which could easily accompany and enrich the knowledge-based learning process. In fact, reductionism does have an unbridled opposite, which both parents and kindergartners abundantly make use of when they tell children about the Sandman, Santa Claus, or the tooth fairy, about treasures at the end of the rainbow or that bird songs assert secret messages (the yellowhammer says "little bit of bread and no cheeese!" and the rosefinch "Pleased to meet you!"). Such imaginative mental pictures and short stories maximize the perception and give additional magic and tension to the words. This *maximism* charges the experience and renews the space for wondering. It signals that the children have entered a world where much is possible and more is to be expected. Maximism may be defined as the use of metaphors, short stories, or personalized make-believe, to enhance imagination and charge the terms with emotions, and thereby personalizing the relation of the child and the world. Maximism is the lightheartedness that characterizes fairytales, children's books, movies, and comics with amazing creatures. It gives Winnie the Pooh to Christopher Robin and Hobbes to Calvin; gives words extended contents, new depth, and new tension, encourages curiosity, and gives wonder a new foothold. One-sided rational knowledge about refraction in raindrops could have the opposite effect on preschool minds: it potentially impoverishes the precepted beauty and could signal that less is to be expected.

The clear-cut, rigorous terms and concepts of adult thinking do not necessarily overlap with those of preschool children. Introduction of new concepts requires awareness of their capacity to grow and develop, and new concepts should be kept in less exact modes than what we are used to as scientists. Steiner (2004) encouraged teachers to apply imaginative and flexible concepts which could grow and develop in line with the child itself. Maximized answers possess this flexibility and open the imagination for further inquiries, reflections, and wondering, and allow the child to attain its own, age-adapted premises. Large, imaginative concepts should accordingly be favored in preschool and gain support rather from cultural symbolism than from strict scientific knowledge.

Moreover, maximism generates subjectivism and promotes friendships with the world. Deep curiosity and the persistent joy of learning in adults are nourished by having inhabited a world populated with friends during early childhood. Lifelong learning commonly rests on the friendship with the things we encountered during the first years of our lives. Without friendships, there is no fruitful learning. And friendships emerge at preschool age from wonder-filled perceptions rather than from knowledge about causal relations. Hence, learning in preschool concerns the following: befriending ladybugs, conkers, pine needles in mud pools, and myriads of other basal perceptive experiences. Maximism confirms a toddler's feeling of inhabiting a perceptually rich and fascinating world where they can make friends,

who widen and deepen reality. Maximism supports friendship—with earthworms, stars, trees, and rainbows (Wagenschein and Berg 1980; Langefeld 1984; Egan et al. 2014). And friendships are not at all knowledge-dependent, but rather rest upon mesmerized innocence, that every preschool child possesses in excess. Naivety makes friends. Before embarking on deep and dedicated learning, friendships accordingly need to be consolidated (Hadzigeorgiou and Schulz 2014).

Needless to say, maximism can be exaggerated, counteracting children's natural yearning for learning and clear-cut facts. But children actually leave the realms of Santa Claus and the tooth fairy on their own (Woolley and Ghossainy 2013), which in most countries coincides roughly with the age of upstart of the primary school. To teach five-year-old children about the imaginary nature of Santa or Winnie the Pooh would deprive them of a valuable step of increased autonomy in conquering this recognition themselves and thereby gaining increased independence.

4 Knowing Things About the World—the Beauty of Diversity

Entering school age, the systematic learning of facts begins and accelerates as puberty approaches. The 9 to 12 years age is characterized by rapid growth of executive functions, responsible for directing, controlling, and coordinating cognitive functions and behavior, in concert with developmental changes in the prefrontal cortex (Welsh et al. 1991). Improved executive functions also manifest themselves in daily life, bringing joy from activities using motor skills, such as cycling, swimming, skating, football, dancing, or games. Increased physical freedom and the mastering of knowledge go along with growing explorative behavior, and during these years, the sense for diversive curiosity flourishes. To relate this to science education requires a distinction between knowledge and science. The two differ in a certain sense, which is easily overlooked but which can be illustrated by the difference between houses and heaps of bricks. Bricks are necessary for architects and engineers who, after complex calculations place them in highly sophisticated ways to create stable buildings. Correspondingly, knowledge bricks is a matter of clear-cut facts, partly empirical and partly conceptual, which need to be established during prepuberty. Science is built on significant amounts of knowledge and indisputable facts, but facts do not necessarily rest on scientific thinking. A solid foundation of facts, however, must be established before analytic and independent thinking is fruitful.

Facts are clear-cut and unambiguous and need to be consciously and systematically learned through exercises, repetition, and memorization. That facts can promote curiosity and wonder might sound unexpected, as adults generally find exercises boring. But the passion for reliable and diverse facts is a striking feature of the human mind during prepuberty. They learn about grammar rules, mathematic formulas, Asian rivers, or baleen whale species with joy, strengthening the cognitive knowledge-based robustness of the pre-teen mind. During early childhood, it was maximism that promoted wondering. Now, the diversity of the world correspondingly stimulates curiosity (Mischel et al. 1972; Kang et al. 2009; Baumeister and Tierney 2011). However, the facts should not yet proceed to science and meta-questions. That step should remain as a half-spoken goal for the state that twelve-year-olds look forward to: that of being a “teenager.”

The claim that inquisitiveness for facts and classical knowledge is especially predominant in the prepuberty is easy to observe. Many scientists will remember how certain interests,

skills, and passions emerged during these years. Children of 10 and 11 years immerse themselves with pleasure into books about all kinds of fact-based certainties. The same age is frequently characterized by the joy of making lists about everything from cars and pop stars to dogs and countries (Takaya 2014). Candy producers are aware of this craving for diversity and put out cards with everything from horses to space shuttles into their packages. Jump rope games rhyme with names of cities, countries, or boy's names and guessing word games reflects the same joy. In classrooms, quiz exercises are well-established parts of learning during the same period (McDaniel et al. 2011; Roediger III et al. 2011). The relationship *between* facts is less important than later, when context and causal relations become essential, constituting frameworks for science. Hence, the guiding idea in stimulating curiosity during the years of prepuberty is to ensure that children are confronted with miscellaneous and clear-cut knowledge of the world, to renew their wonder and curiosity for the diversity of the world they inhabit.

The learning of facts provides children with a valuable sense of achievement, where they still trust unambiguous knowledge. Facts have this very quality—*a spade is a spade*. Yet they offer the joy of exercise and training, too—the joy of challenges to master. Whether soccer, ballet, chess, or riding, the feeling of proficiency increases as puberty approaches, as the reality of adult life becomes closer, with the teenage years being its entrance point. Exercise establishes a firm basis for knowledge, which anchors the mind and brings the joy of certainty, constituting a foundation for upcoming science. In addition, the preschool passion for wonder should possibly be maintained by means of esthetic exercises (Burton et al. 1999).

Facts can easily be contextualized without going fully into scientific analyses, for instance, by focusing on the historical struggle for reliable knowledge. The great explorers (Magellan, Marco Polo, Columbus) or pioneers of science like Ignaz Semmelweis, Marie Curie, Michael Faraday, or Henrietta Leavitt illustrate how knowledge is the fruit of the doubts and strivings of individuals, sometimes even outsiders, who had to struggle with the prejudices of their contemporaries—habits of minds which many children during this age may easily recognize (Lin-Siegler et al. 2016).

Gradually, however, school subjects must involve increasing elements of science, with its emphasis on complexity and ambiguity. Now, the time comes closer where wonder and diverse curiosity should fuse and manifest as epistemic, knowledge-based, and deep curiosity, which must fully invade the intellectual realm of the mind. Knowledge itself becomes the source for wonder. The students are ready for science.

A pedagogy aiming at promoting lifelong, knowledge-based curiosity will thus emerge from wondering and maximism in preschool, promoting friendships with the world, turning towards the learning of facts and clear-cut knowledge during the years of prepuberty, and so assembling a firm foundation for real science education during adolescence.

5 Science and Knowledge-Driven Curiosity

Puberty is mainly considered a matter of sexual maturity. But its significance for the emotional reorganization of the personality is possibly of even greater importance (Erikson 1994; Rosenfeld and Nicodemus 2003; Christie and Viner 2005). The brain's frontal cortex grows significantly (Rosso et al. 2004), cognitive processing and intellectual functioning speed up, and executive functions including abstract thought, organization, decision making, and planning are consolidated (Yrgelun-Todd 2007). The personality is rebuilt and redefined, often

taking quite unexpected directions (Abbott and MacTaggart 2010; Santrock 2014). Self-images are distorted and doubts come up about beliefs and assumptions that had been previously taken for granted. While childhood is characterized by identification with adults, it is from that point on more urgent to identify with oneself—a challenging and confusing process, both for the subject and for the surroundings, as the self is volatile and unstable (Diorio and Munro 2003; Susman et al. 2007). The world is not as assumed, the accustomed reality becomes disputable, and familiar words and terms suddenly appear ambiguous. Puberty is a period of revelation and disclosure—*what is true?* This makes puberty the perfect mindset for anticipating science. Facts and clear-cut terms can be crammed and learned by retrieval. Science cannot. Science needs to be discovered and even conquered by the skeptical individual through critical efforts. In puberty, deep curiosity and intellectual wondering potentially become a matter of existential importance. Kieran Egan's claim "The educational achievement is not to make the strange seem familiar, but to make the familiar seem strange" (Egan 1986, p. 47) has never been more relevant than now.

It is, however, difficult to see how contemporary science textbooks meet this adolescent state of mind. Rather, they tend to convey science as blocks of facts and scientists as unified through a sound understanding of every single topic, with little room for unsolved problems, inconsistencies, and doubts (Berg et al. 2003; Zion and Sadeh 2007). Students' questions in the classroom are too often met with objections like "This isn't part of the curriculum" or "Now you're more into philosophy," and the exploration of paradoxes and uncertainties is rarely encouraged (Ciardiello 2006). Yet every scientist knows how far such a view is from reality—and fortunately so. Scientists are deeply puzzled by unsolved questions: in biology, reaching from the causes for protein folding and epigenetics to the origin of life and the causes of sex; in physics, reaching from dark energy and Higgs bosons to gravity and features of the Kuiper belt; in geoscience, from the Cambrian explosion to the space problem of plutons; in neuroscience, from consciousness and free will to the reasons for sleep and neural plasticity; and in medicine, from cancer to the roles of gut bacteria (Maddox 1998; van Hemmen and Sejnowski 2006; Shklyadrevsky 2013; Fischer 2014; Allen and Lidström 2017).

Astonishingly, few of such open-ended questions are included in textbooks or in science education. At adolescence, where curiosity and wondering should be stimulated by the great unsolved questions of science (Dawkins 1998; Lindholm 2012; Fischer 2014) and the students are fully capable of comprehending paradoxes, science is frequently conducted not with wonder and curiosity, but with facts. This results in simple, clear-cut answers of reduced complexity. Paradoxes and inconsistencies are concealed. The journey of individual conquest, which is essential for any scientific understanding, is substituted by obligations of learning-based "belief in science," where students are exposed to scientific facts that they feel must be taken for granted, without any room for doubt or new curiosity (Østergaard 2017). The same worry was expressed by Dawkins (1998): "Far from science not being useful, my worry is that it is so useful as to overshadow and distract from its inspirational and cultural value. Usually even its sternest critics concede the usefulness of science, while completely missing the wonder." (p. xii). Science possesses this Janus-face: One side concerns results, facts, and scientific paradigms, whereas the other side is the open-ended questioning and exploration of the big unknown. As pointed out by Brian Cox (2011), p.5 "the practice of science happens at the border between the known and the unknown." And Edward O. Wilson (2013, p. 47) characterized the ideal scientist as somebody who thinks like a poet and only later works as a bookkeeper. While the bookkeeper side is more easily achieved in classrooms, the poetry side is mainly left uncultivated, despite its crucial importance for scientific development. We are

accordingly in urgent need of educational methods that ensure its wellbeing in educational institutions.

A core problem of high school science education is the exaggerated use of models (Coll et al. 2005; Giere 2004; Lindholm 2017a). Models aim to simulate causal relations and are indeed indispensable for scientific understanding. Yet, they present an ontological problem in classrooms that is mostly overlooked: the temptation to confuse models with reality. Instead of treating models as simplified illustrations of a hypothesized mechanistic relation, they are presented as the reality. Most textbooks rather describe “model realities” where real-world examples are “cherry-picked” to confirm the model. Most students, and unfortunately a considerable number of science teachers too, perceive science as a set of defined and clear-cut truths, which pretend to deliver consistent and satisfying explanations about literally everything a teenager could possibly be puzzled by.

Such a conception of science does not necessarily encourage deep curiosity. But a feature of models is their “explanatory power,” which imply cases not consistent with the model. And these cases are especially relevant for renewal of curiosity, as they fail to perform as predicted by the model. One-sided emphasis on models could accordingly counteract students’ growing curiosity. Instead, they find themselves overwhelmed by the belief that “everything is explained” and by a science lacking any personal relevance for their own lives (Lidley 1993; Horgan 1996, 2004). Models are valuable, but are provisory scaffolds for assumed structural and causal relations. And science is, not least, a history of new models of higher explanatory power, which have displaced former ones. In fact, models tend to go through certain developmental phases, moving from a pioneer stage, gaining increased attention and rapid development, followed by a period of general acceptance, after which they are gradually left and substituted by novel, complementary views—not because they were shown to be wrong, but because more was to be said on the issue than firstly assumed.

In fact, the term “paradigm shift” does not necessarily reflect historical realities (Nussbaum 1989; Fischer 2014). Einstein’s theory of relativity was not a rejection of Newton, and classical physics are still part of the curriculum, but the entire discipline experienced a profound extension. And the theory of natural selection does not mean the same today as it did for Darwin (Mayr 1982; Zimmer 2001; Lindholm 2015), which by no means is to say that *The Origin of Species* was “false.” Linné’s *Systema Naturae*, likewise, is still part of the life sciences, although the term “biodiversity” has evolved considerably since 1758. Scientific knowledge is not a matter of static and quantifiable units. It evolves (Siegfried 2005), parallel to the students themselves. To recognize the limits of models is not to relativize knowledge, but to acknowledge science as a process (Pintrich et al. 1993; Fischer 2014).

The significance of these perspectives should be open-heartedly discussed with students because it legitimizes their own wonder, renews their curiosity, and enables knowledge gaps to be filled. Models do not nourish deep curiosity because they solely facilitate questions that can be answered within the framework of itself. Indeed, nothing is wrong with such model-framed questioning; however, to neglect inconsistencies and paradoxes is to counteract knowledge-based wondering and make brains tired, as students are fully aware that such questions do not lead to new scientific problems. Model-framed questioning cannot generate other perspectives than those explained by the models themselves. Framing science with models therefore unavoidably delivers final and satisfactory answers, which do not leave anything unanswered behind. Model-based explanations do not generate a new *But...?* because the very nature of models is to generate consistency. Models keep the thinking literally “inside the box,” and the careless use of

models in science education is hence a potential threat against the scientific project itself (Box 1979; Scharrer et al. 2016).

Models are indeed mandatory in science education. But when the students have gained an understanding of the model and had time to explore and enjoy its explanatory power, the teacher needs to perturb the harmony by pointing to data that are inconsistent with the model. It is indeed necessary to give students final and closed model-based answers, to make them familiar with the topic and the state of scientific understanding on the subject, and such answers create transparency and confidence in the discipline. But answers which lead to new questions are of equal importance and, for the reasons given above, they cannot come from models. Answers which yield new questions depend on breaking out of the structures framed by models, and move into the empirically complex, wonder-full, and beauty-full reality (see box).

Closing or opening answers—two examples from biology

1. If a dominant male lion dies and a new one takes over the herd, it will sometimes aim to kill the extant cubs. This example of so-called infanticide is frequently used in textbooks and classrooms, as it fits well into the model of organisms as genetic-driven systems, suggesting that the practice favors those offspring that carry their own genes. If left alone, the lion example only illustrates the model of the genotype superiority and precludes any further questioning. In reality, however, adoption is at least as common as infanticide, not only among lions, but also among other mammals and birds. Adoption was previously mainly observed among livestock and pets, but is now a well-established fact even in the wild. Several duck species (i.e., the shelduck, *Tadorna tadorna*, or the eider, *Somateria mollissima*) frequently adopt chicks of other females, and among penguins, approximately 20% of the offspring are adopted. Even inter-specific adoption has been observed. The causes of this behavior are ambiguous, which just underpins its educational value. After making students familiar with the model of genetic “egoism,” sharing the phenomenon of adoption contradicts its universality. By maintaining a balance between convincing examples supporting the model, deep knowledge-based curiosity is ignited by pointing to inconsistencies of the same.
2. Sex is commonly thought as an important driving force for evolutionary novelties, due to its great ability to maintain genetic variation. Sexual reproduction has indeed been a vital source for variation ever since its advent during the Precambrian. However, the evolutionary implications of sex mostly remain uncommented upon in classrooms, although they are as puzzling as they are fascinating. Firstly, one must realize that natural selection usually is considered exclusively to address fitness of individuals, and not of populations. The only thing which matters is the number of reproductive offspring of the individual, relative to the others. And the costs of sex for the individual are immense, in terms of maintaining reproductive organs, energy allocation, exposure to diseases and predators, mate finding, and courtship. Individuals would double their fitness by means of asexual reproduction. Males pose particular challenges because they do not reproduce at all but still consume resources. Hermaphrodites could possibly avoid this dead end, but this solution is surprisingly rare. We still lack a sound explanation for the evolutionary paradox of sex, which is well acknowledged among researchers (“the queen of problems in evolutionary biology”), but which rarely finds its way into classrooms—despite its perfect properties for promoting curiosity and renewed knowledge-based wondering.

Teaching science is therefore a question of balance between empirical phenomenology and theory-generating models (Østergaard 2017), where empirical elements need to be as mandatory as models, and not just “cherry-picked” to serve the latter. Answers which lead to new questions must come from outside the box, from the refreshing and confusing reality. The power of reality is a necessity in science and reminds us that all models are preliminary (Hadzigeorgiou and Schulz 2014), but how to balance models and reality is rarely discussed in science education. The result is that a disappointing high number of students leave high school with learned and not explored scientific knowledge, making them indifferent towards scientific approaches in general, as the knowledge they gained was acquired by means of memorization rather than through curious and critical thinking.

Concepts aiming to develop a methodology to promote curiosity and wonder are rare (Egan et al. 2014; Lindholm 2017b), and there is a dearth of studies in science education. Hadzigeorgiou (2012) found that an enhanced sense of wonder in 9th grade physics made a

substantial contribution to the learning process, by promoting more conscious learning and increased personal involvement. Gilbert and Byers (2017) recently explored effects of wonder and curiosity-based methods in preservice elementary teacher conceptions of science. A large share of the students had negative memories of science curricula and were accordingly worried for their own ability to teach science subjects. The study found that increased focus on curious questioning and wonder was a catalyst for both interest in science and the development of pedagogical courage to take on science teaching: “The chance to wonder without boundary or fear of reprisal brought about the possibility that these [students] might venture closer to the kind of thinking that inspires scientists” (p. 922).

The pedagogical theory that most explicitly has given space for wondering and deep curiosity is probably those of Waldorf schools, in aiming to connect esthetics, emotive aspects, and art to the science curricula. Waldorf preschools favor maximism, and phenomenological approaches are favored in high school science education (Østergaard et al. 2008; dos Anjos et al. 2012). Interestingly, Waldorf school students appear to perform better in joy of knowledge, are seemingly less brain-tired, and get more easily involved in new subjects in high school (Ogletree 1996; Dahlin 2007). Moreover, Waldorf pedagogy keeps the focus on general human education and “Bildung” in a broad context, recognizing the value of science and knowledge for its own sake (Hadzigeorgiou 2015).

6 Conclusion

Deep curiosity is an essential factor as a driving force for societal and scientific growth, and to maintain its development and wellbeing throughout childhood in science education is an urgent task. In preschool, curiosity should be nourished by means of maximism, which encourages children to inquire and wonder. A benefit of this method is friendship with the natural surroundings, which in turn constitutes the foundation for acquiring facts at school. In prepuberty, on the other hand, curiosity should come into focus, by means of learning about the diversity of the world, based on facts and terms. Finally, emotive friendships and a basis of facts and clear-cut knowledge are the suitable substrates for the deep epistemic curiosity and personal understanding of science, which should dominate during the years of adolescence and high school age.

This means achieving the transition from naïve preschool “nature-friendship,” to prepuberty “nature-knowledge” and then during adolescence the maturation into “nature science.” The child is then equipped with established terms and concepts and an inquiring mind, ready to begin a bold search for new insights and truths, which constitutes the foundation for any science. The progress from maximism to fact-based knowledge and to science demonstrates a possible pathway to maintain the joy of learning and deep curiosity throughout an entire life span. Maximism creates friends. Knowledge creates confidence. Science creates doubt. Although science rests on facts, it is permanently doubting its own findings and models. Thus, science education must have the personal journey of discovery as goal.

This is what Richard Dawkins had in mind when stating that “Science is the poetry of reality.” The quote captures what must be at the core of any science education. It reflects the experience of the independent and mature self, where curiosity is not merely a pale memory from a lost childhood, but the impetus for reflection, science and knowledge in the intellect of the adult.

Compliance with Ethical Standards

Conflict of Interest The author declares no conflict of interest.

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