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Physics for Society in the Horizon 2050

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Chapter 8

Science for society

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8.1 Introduction

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8.2 Education and research in an interdisciplinary environment

During the second part of the 20th century, the social contract between science and society was merely a tacit agreement foreseeing that public money would finance the research that would sustain technology development and innovation and enhance the socioeconomic well-being of our society. The spheres of science, politics, and society were largely separate.

In the last 25 years, this model has been broadly questioned. Blurred ethical standards and catastrophes in addition to the dissemination of 'fake news' have repeatedly undermined some people's faith in science. Innovation has not always been driven by the common good or the needs and expectations of the citizens. Most important, there has been increasing awareness that the world is facing drastic new challenges, from climate change and food security to migrations and energy supplies, which will determine its future.

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Against this background, a new normal is arising. It involves the interplay of all sciences, including natural, social, and human sciences, without which societal challenges cannot be solved. Education and training must be rethought to foster interdisciplinarity and transdisciplinarity. A democratic governance of science and innovation will, while protecting the inspiration and creativity that drives research, facilitate the participation of all stakeholders in developing choices and processes. Citizens will have greater expectations regarding communication and accountability from scientists at a time when the Internet revolution and social media make it possible for all to access, understand, and share knowledge and scientific data. At the dawn of the open science era, we are seeing the benefits of information technology and artificial intelligence (AI) in consolidating and speeding up the research and innovation process. Finally, we must have trust between citizens and science, conditioned by aspects of research such as ethics, integrity, and transparency.

A global goal is to generate the new knowledge that will help us to better understand and address the major challenges of our time and facilitate the transfer and integration of scientific findings into politics and society. But science has its own limits, whether theoretical, experimental, ethical, or philosophical.

All these issues that will determine the future of scientific research—and *ipso facto* of humankind—are addressed and discussed in this chapter by a panel of prominent contributors. The chapter is divided into five main sections: *Education and research in an interdisciplinary environment*, *Science with and for the citizens*, *Open communication and responsible citizens*, *Science and ethics,* and *Limits of science*.

8.2.1 The future of physics education

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8.2.1.1 Introduction

Physics for Society at the Horizon of 2050 will focus on addressing societal grand challenges and enabling individuals and societies to prosper in a globally connected society. The Physics Education Division of the European Physics Society has identified physics education as vital to ensuring active citizenship in democratic societies, as well as for supplying and training a wide range of scientists and engineers. This mission is echoed in the Organisation for Economic Cooperation and Development (OECD) Learning Compass 2030, an evolving learning framework that sets out an aspirational vision for the future of education [1]:

> *How can we prepare students for jobs that have not yet been created, to tackle societal challenges that we cannot yet imagine, and to use technologies that have not yet been invented? How can we equip them to thrive in an interconnected world where they need to understand and appreciate different perspectives and world views, interact respectfully with others, and take responsible action toward sustainability and collective well-being?*

The learning compass (figure 8.1) offers a vision of the types of interconnected competencies that students will need to succeed in 2030, namely, knowledge, skills, attitudes, and values. The concept of student agency—defined as the capacity to set a goal, reflect, and act responsibly to effect change—is central to this framework. This concept is rooted in the principle that when students are agents in their own learning, they are more likely to have 'learned how to learn', an invaluable skill that they can and will use throughout their lives.

It is widely recognised that individuals who have studied physics are eminently suited to roles in a wide range of jobs, industries, and organizations; therefore, their physics education needs to support the development of interconnected competencies across the domains of knowledge, skills, attitudes, and values. Over the past decade, physics curricula in schools, colleges, and universities have adopted learning goals

Figure 8.1. Organisation for Economic Cooperation and Development learning compass 2030 [1], reproduced courtsey OECD (OECD, 2019).

that involves developing student's scientific abilities, skills, and competencies alongside physics-specific knowledge. It is less common, however, for physics programmes to explicitly consider knowledge and skills associated with the application of physics in interdisciplinary contexts and in the wide variety of career settings in which many graduates find themselves [2]. Crosscutting, interdisciplinary connections are becoming important features of future-generation physics curricula and define how physics should be taught collaboratively along with other STEM disciplines. Recent studies highlight that an integrated approach to STEM education can be effective in supporting students to develop a range of transversal competencies such as problem solving, innovation and creativity, communication, critical thinking, metacognitive skills, collaboration, self-regulation, and disciplinary competencies [3]. Indeed, individuals' long-term professional success is often attributed to their having developed transferrable skills that can be applied in diverse career directions.

8.2.1.2 Pedagogical practices in physics education

Despite the frequent use of a variety of representations, such as graphs, symbols, diagrams, and text, by physics teachers, educators, and researchers, the notion of using the pedagogical functions of multiple representations to support teaching and learning is still a gap in physics education. Studies have shown that when students use representations in multiple formats during the learning process, their conceptual understandings of physics concepts as well as their problem-solving skills are enhanced [4].

While psychologists and educational scientists seem to converge on the notion that student involvement is critical to successful learning, there is much debate around how students should be facilitated in the learning process. Bao and Koenig [5] report as follows:

> *Based on a century of education research, consensus has settled on a fundamental mechanism of teaching and learning, which suggests that knowledge is developed within a learner through constructive processes and that team-based guided scientific inquiry is an effective method for promoting deep learning of content knowledge as well as developing high-end cognitive abilities.*

In disciplines such as physics, inquiry-based learning (IBL) has been promoted as being a more effective pedagogical approach compared to more expository instructional approaches—as long as learners are supported adequately. John Dewey developed the model of learning known as 'the pattern of inquiry' and was the first to use the word inquiry in education: 'Scientific principles and laws do not lie on the surface of nature. They are hidden, and must be wrested from nature by an active and elaborate technique of inquiry' [6]. Distinct levels of inquiry instruction have been described in terms of the level of student guidance, for example, structured, guided, and open inquiry. Research conducted on the effectiveness of IBL pedagogy emphasises that guidance is pivotal to successful IBL at all levels; learners who are given some kind of guidance act more skilfully during the task, are more successful in obtaining topical information from their investigational practices, and score higher on tests of learning outcomes administered after the inquiry [7]. These benefits are largely independent of the specificity of the guidance. Even though performance success tends to increase more when more specific guidance is available, learning activities and learning outcomes improve equally with specific and nonspecific types of guidance. Interestingly, the effectiveness of guidance is shown to apply equally to children, teenagers, and adolescents; this finding offers physics educators scope to design effective IBL learning opportunities at all educational levels.

8.2.1.3 Strategies for assessment of learning in physics education

While there is growing agreement on the competencies individuals should possess as well as the pedagogies to develop them, there is still much debate about what strategies are effective in assessing these competencies. There are multiple forms of assessment that vary depending on the purpose they are intended to serve. Common forms of assessment include the assessment of student performance through high-stakes exams or through collection of information about students' achievement with the intent to assign a grade, usually at the end of instruction. These are examples of summative assessment in the sense that their purpose is to provide evidence of learning after instruction. Formative assessment, by constrast, is centred on (1) the collection of useful assessment information through appropriate means, (2) the meaningful interpretation of the assessment information, and (3) the process of acting on the interpretation of the assessment information to enhance teaching and learning while they are still in progress [8].

The use of formative assessment has received much recognition as a powerful means of enhancing students' learning in physics. In particular, the use of self-assessment and peer assessment is considered essential in achieving honest collaboration, critical thinking, and respect between learners. Feedback is an indispensable component of formative assessment and is considered pivotal to its potential effectiveness. It is important to emphasise that feedback needs to be formative in that it should extend beyond merely indicating performance (success/failure) to explicitly seeking to influence students' subsequent actions in a manner that should facilitate learning. Interest in digital formative assessment has grown rapidly in the past two decades for several reasons, including the provision of feedback in a timelier manner, the assessment of hard-to-measure constructs and processes that were previously inaccessible, the inclusion of new item types capable of providing more nuanced information about learning, automation of the feedback process, access for students with disabilities, and greater opportunities for student collaboration.

However, a critical barrier to the use of effective strategies for assessing student learning in physics across range of competencies (knowledge, skills, attitudes, and values) is teachers and students' engagement and competence with assessment and feedback practices. There is an urgent need to provide tailored professional learning opportunities and resources for teachers of physics as well as explicit support and guidance for students on how to productively engage in assessment. If physics education is going to contribute to a connected and complex society, educators and researchers needs to collect and disseminate more evidence about what are effective teaching and learning processes in physics. This will require further development and sharing of valid and reliable assessment strategies and tools for assessment of a range of 21st century competencies.

8.2.1.4 Equity and inclusion in physics education

There is increased emphasis on the need for schools and education systems to provide equal learning opportunities to all students. Equity does not mean that all students must obtain equal outcomes but rather that, provided with the same opportunities, differences in students' outcomes are not driven by individual factors such as gender, race, socioeconomic status, immigration background, or disabilities [9]. For example, the socioeconomic status of students' families is widely recognised as a reliable predictor of student academic performance and, indirectly, success in life. There is a growing body of evidence showing that gender stereotypes—both implicit and explicit—affect engagement and professional interactions of women in physicas and affect their careers [10]. Recent studies have focused on how a student's sense of belonging in physics can be adversely affected by intersections of these factors, such as interpersonal relationships, perceived competence, personal interest, and science identity.

Statistics compiled by the American Physical Society indicate that women typically represent only 20% of undergraduate and postgraduate physics student cohorts [11]. Given the historic and continued underrepresentation of women in physics, it is important to understand the role that secondary-level physics education plays in attracting young women to physics degrees and careers. An examination of women's experiences in high school physics education has identified three key barriers to their participation: students' perceptions of the field and what type of person practices physics, their personal experiences of learning physics, and their experiences with gender and physics identity. Ultimately, these barriers to young women's self-efficacy, competence, performance, and recognition in physics inhibit their developing a physics identity and often result in their lack of participation in further physics studies [12].

What is being done to address the gender gap in physics? The American Physical Society has partnered in a US national movement [13] to promote physics identity development and empower high school teachers to recruit women to pursue physics degrees in higher education. Initial studies from this intervention report significant changes in high school students' physics identity, that is, their recognition beliefs (feeling recognized by others as a physics person) and beliefs in a future physics career. In the UK, the Institute of Physics (IOP) has reported that there has been very little change in the proportion of girls studying physics at the upper second level over the past 30 years [14]. To tackle this issue, the IOP has implemented programmes to improve gender balance in England, Scotland, Ireland, and Wales through collaboration with schools and education–research partnerships. These programmes have facilitated professional learning opportunities for teachers to develop their knowledge and awareness of physics careers, unconscious bias, and

Table 8.1. Tackling the misconceptions that affect gender balance in physics [15].

- There is more variance within groups of boys and within groups of girls than there is between boys and girls. Gender differences are learned, not innate.
- One group should not be preferentially treated compared to any other group.
- Unconscious bias and normalisation of stereotypes means that there are often unspoken barriers.
- One-off activities or interventions do not have a lasting impact. They need to be part of a wider strategy.
- Role models can have a positive impact but usually only where there is an ongoing relationship.
- A teacher's gender does not have a large influence on subject choice. The majority of students respond to good teaching, irrespective of whether the teacher is male or female.
- Attempts to make a subject more appealing by reinforcing a stereotype are unlikely to be effective.

inclusive teaching approaches. Through these programmes, schools are supported to address equity and inclusion in physics education by tackling common misconceptions (as presented in table 8.1). The findings of these programmes emphasise the importance of raising awareness in schools of the inherent barriers that learners face in accessing opportunities.

Some of these barriers to participation in physics may be alleviated through recent technological developments that provide digital ecologies and create respective ecologies in education. Such ecologies can enhance teaching, learning, and assessment by offering innovative and inclusive learning opportunities for students that would otherwise be difficult to achieve and can result in physics education becoming more equitable and inclusive.

- Physics curricula

  Over the last three decades, physics education research has provided substantial evidence of the impact of innovative teaching, learning, and assessment strategies on the development of physics understanding and competencies. However, the uptake of physics in schools, colleges, and universities continues to be less popular than that of other natural sciences, and physics suffers from a stigma of being a science that is very mathematical, abstract, and complicated. Physics is a core pillar of all natural sciences; it is about understanding the basic laws of nature and explains how the world around us and within us functions. This fundamental understanding of physics is often not appreciated by students, and physics curricula in schools need to evolve to address this issue. The use of investigative and inquiry-based learning approaches is strongly encouraged for introducing physics concepts, starting with our youngest learners. Such approaches can support learners to 'learn by doing' and develop their knowledge and understanding of physics through real-world examples. In this way, physics education will play an important role in underpinning the development of STEM knowledge and competencies required in later curricula.

While efforts to update physics curricula in schools has gained momentum over recent decades, in many cases, contemporary and modern physics topics are introduced only by using a reductionist approach at the end of a curriculum in topics such as special relativity, particle physics, quantum physics, and liquid crystals. The particle physics community believes that exposure to particle physics and its technological applications increases the interest of students in physics and can change their perceptions of the role of physics and physicists in today's society [16]. Many physics educators emphasise the urgent need for collaborative research to design coherent learning paths and scaffold student's conceptual development in modern physics topics [17]. The inclusion of contemporary and modern physics topics in school curricula offers an opportunity to provide authentic and engaging learning experiences for students and ultimately change their perceptions of the role of physics and physicists in society.

- Supporting physics teachers

  It is broadly recognised that the quality of an education system is highly dependent on (1) getting the right people to become teachers, (2) developing them into effective educators, and (3) ensuring that the system is able to deliver the best possible education for every child. However, the lack of qualified teachers of physics in secondary-level schools is a matter of international concern.

  A new report from the American Physical Society prioritises actions to be taken to ensure that the US continues to be a global leader in science, technology, and innovation [18]. These include policies to 'address the urgent shortage in qualified STEM teachers, so that aspiring STEM-professionals have the opportunity to join the workforce of the industries of the future and eliminate hostile workplaces and pathways to all that want to contribute to innovation and a better society'.

Over the past two decades, the OECD Directorate for Education and Skills, together with its member and partner countries, has collected significant volumes of data on teachers, school leaders, and students that allow educators and policymakers to learn from the policies and practices that are being applied in other countries. The 2021 OECD report presents combined data collected from both the 2015 Programme for International Student Assessment (PISA) and 2018 Teaching and Learning International Survey (TALIS) [9]. This report highlights that since PISA was carried out in 2015, expenditure on schooling has climbed steadily. However in 2018, PISA showed that students' performance scores in reading, mathematics and science in the Western world have flat-lined. In particular, this report highlights the following:

> Teachers and schools make an important difference to how a student performs and feels. More specifically, it is the time teachers spend actually teaching in class, not disciplining or taking care of administrative work, and the hours they spend marking and correcting work, and

going over this feedback with their students that links to how well students do academically, and how motivated and optimistic they are about their learning and prospects.

The report highlights the presence of differential effects across subjects, as teachers' satisfaction with their work environment seems to be more closely related to student performance in science than in reading and mathematics. While this may be explained by the fact that, unlike reading, students mainly acquire their knowledge in science at school, it also recognises that requirements such as a well-equipped school lab are critical for science teachers to supporting student learning in science [9]. A critical review of the role of laboratory work in physics teaching and learning presented by Sokołowska and Michelini [19] highlights the essential role of laboratory work in supporting and extending student learning in physics, that is, conceptual understanding, creativity, metacognition, modeling, and problem-solving skills. Fostering collaboration between researchers and teachers to design interactive learning environments, such as augmented or virtual reality laboratories, can also provide unique opportunities to deepen student's understanding and engagement with both fundamental and contemporary topics in physics. However, the widespread adoption of these approaches in classroom practice is highly dependent on teachers' competence and confidence in designing appropriate learning opportunities. Appropriate and sustained professional learning opportunities need to be provided for teachers to extend and deepen their own content knowledge for teaching physics. A variety of models have been proposed for physics teacher education. Recent strategies advocate supporting teachers collaborating as part of a professional learning community to carry out practitioner inquiry on their own practice.

8.2.1.5 Conclusion

In conclusion, several actions are needed to refocus the vision for physics education in Europe so as to make valuable contributions to Physics for Society at the Horizon of 2050. These changes need to be embedded in all education levels, from early childhood to higher education, and careful attention needs to be given to supporting learners across educational transitions. First, physics curricula and pedagogies need to be revised and focus on the development of competencies across the domains of knowledge, skills, attitudes, and values. Second, strategies for achieving equity and inclusion in physics education need to be adopted in classroom practice. Third, interdisciplinary collaboration between physics educators, researchers, and policy-makers is critical to attracting and supporting future generations of both physics students and physics teachers.

8.2.2 The challenges of physics education in the digital era

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8.2.2.1 Introduction

In this section, we consider the impact on physics education of the rapid development of digital technology, looking at challenges and opportunities in teaching, assessment, and experimental work.

Technological progress has changed the types of employment for which we are preparing students as well as their expectations and aspirations. Scientific equipment depends increasingly on electronics and computerisation, and students need skills that are appropriate for a data-rich world. Scientific investigation is an ideal platform for developing transferable skills such as IT literacy, programming, scientific communication, and collaborative working, all highly valued by employers.

Education has increased its use of digital technology, and the global response to the COVID-19 pandemic has accelerated the pace of change with lasting effects. Physics educators should be prepared to understand and respond to new technologies as they emerge.

8.2.2.2 Digital teaching and learning

While distance-learning institutions such as the UK Open University (OU) have used online tuition for some time, many other providers moved to online teaching during 2020, thanks to the widespread availability and adoption of online videoconferencing. Many students are now familiar and confident with online collaboration tools in other settings, leading to a better acceptance of this technology in educational context.

However, many challenges remain. Computer equipment and the Internet are not accessible to all students and educators, or equipment might be obsolete with bandwidth and reliability issues. Digital technology can enhance learning capabilities for some students but create barriers for others. We anticipate that these difficulties will reduce towards 2050 as stable platforms with high-bandwidth connectivity become more widely available. AI will certainly solve accessibility issues, for example, by enabling accurate real-time captioning.

Students and educators frequently have concerns regarding feedback and interactivity in an online setting. However, videos, interactive activities, and quizzes as well as text chat in videoconferencing platforms enable students to participate in discussions with more confidence.

We advocate a blended approach, mixing the strength of online delivery with more conventional methods. Using printed materials in conjunction with onscreen study can reduce the cognitive load on learners, making learning more efficient and leading to improved outcomes [20]. The study process is increasingly taking place on a wide range of digital devices, including tablets and e-readers, and improvements in these technologies may reduce the gap between online and paper-based reading and learning [21].

Students' perceptions and expectations of online study are important, as they can affect their performance on science modules. Onscreen study skills can be better developed if students are exposed early to online materials and activities. A sense of community and involvement with peers can be built through online tutorials and discussion forums and through collaborative working in group projects and remote experiments [22]. This is especially important in an entirely distance-learning environment, where students are unlikely to have access to traditional laboratories and classrooms.

Online teaching has considerable benefits. Analytics can be used to gather statistics on students' interaction with online content, allowing us to better understand their progress and to personalise educational materials and activities. By eliminating the need for travel, international students and students who are housebound or in remote locations can participate equally, without the financial and environmental cost of traveling. Thoms and Girwidz [23] describe a virtual remote laboratory that combines the benefits of remote experiments, interactive screen experiments, and simulations via live internet connections or offline. The Global Hands-on Universe project [24], which includes the Galileo Teacher Training Programme, is an example of an international initiative making online science investigation accessible in less developed countries. It provides tools, software, and teacher training materials free of charge to locations with fewer resources and encourages participation in international scientific projects.

8.2.2.3 Digital assessment

Digital assessment usually involves multiple-choice quizzes. These bring the advantages of apparent objectivity, reduced marking time, especially for large classes, and rapid feedback. Multiple-choice quizzes can be used to trigger deep learning, for example by way of peer instruction [25]. However, such quizzes pose a number of challenges for physics educators. They have limited scope in assessing written or mathematical exercises, raising the question of whether correct answers indicate genuine understanding or guesswork.

Technological and pedagogical developments have extended the potential of computer-marked assessment beyond multiple-choice questions. Systems using computer algebra to mark and give feedback on algebraic responses and systems that mark free-text written answers are readily available [26]. Technology can be used to enhance the assessment of student learning in many ways, including online submission of assignments, feedback delivered by audio or video, and e-portfolios for assessment.

8.2.2.4 Experimental work

Traditional labs with students working onsite and interacting directly with experimental equipment are increasingly replaced by online remote experiments, as is done in many real-life scientific investigations. Indeed, today many researchers can work and acquire data on a particle accelerator or a telescope remotely. Thus, many of the skills developed by students on remote experiments are directly relevant in modern research environments.

An early example of a physical experiment in progress is a spectroscopy interactive screen experiment (ISE) [27], where students use real experimental data based on hundreds of photographs of a physical experiment. ISEs were designed to supplement other methods for teaching experimental physics and to help people with disability, illness, or other employment or caring responsibilities. ISEs also provide additional practice for students to complement conventional experiments.

8.2.2.5 Remote experiments in physics

In contrast to ISEs, true remote experiments involve real equipment operated via an Internet connection. Video and software feedback enable live interaction with real-time control of experimental equipment and collection of data.

Two experiments offered to undergraduate students at the UK OU illustrate the current state of the art in remote control. The first is a traditional Compton scattering experiment; the second is an infrared (IR) spectroscopy experiment involving up-to-date space science technology.

8.2.2.5.1 Compton scattering

In the online Compton scattering experiment (figure 8.2), x-rays from a tube are scattered by electrons in a Perspex acrylic target and captured by a solid-state detector on a rotatable arm. Spectra are analysed to confirm the change in x-ray energy versus angle. In doing this, students obtain the experimental evidence that photons carry a momentum of $p = h/\lambda$, thus confirming a fundamental relationship in quantum mechanics.

8.2.2.5.2 Planetary atmosphere gas cell

The hardware for the newer planetary atmosphere gas cell experiment employs a system of valves allowing analysis of different gas mixtures representing possible planetary atmospheres. The thermal valve, originally developed for the Rosetta exploration mission, controls the pressure of the gas cell where the infrared spectroscopy takes place. Students gain experience with components from actual space missions and learn experimental design and control techniques (figure 8.3).

8.2.2.6 Benefits and drawbacks of remote experiments

The advantage of remote experiments is that they offer access to more advanced and ambitious equipment and can be operated outside regular laboratory or teaching hours. UK OU students have also access to professional optical and radio telescopes and even to a Mars rover facility where teams can control a custom-built rover in a recreated Martian landscape, following protocols modeled on NASA mission operations.

Remote experiments enable students to work with hazardous materials and environments, such as radioactive sources, x-rays, and compressed gases. Health, safety, and risk assessment are built into planning and teaching materials. Thus

Figure 8.2. Compton scattering remote experiment. Computer interface with webcam view, control and status panels with setting parameters, and data display.

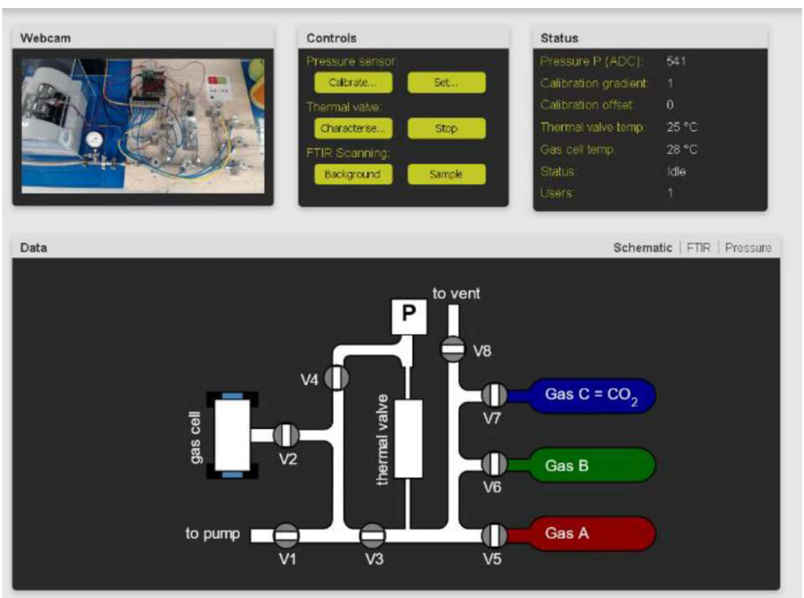

Figure 8.3. Control interface for IR spectroscopy of various gas mixtures. Computer interface with webcam view, control and status displays, and interactive representation of the experimental setup. Spectra are downloaded for analysis as in the Compton experiment.

students are educated in experimenting within safe limits, considering the safety of the personnel operating the actual equipment.

One drawback or concern relates to the effectiveness of remote training experiments regarding the development of procedural skills as compared to direct hands-on manipulation.

Other benefits and drawbacks are summarised in [28], where the authors conclude that well-designed online laboratories can be as effective and motivating as traditional ones if experiments are involving, interactive, and engaging. Dintsios *et al* [29] reported an increased acceptance of remote experiments among secondary students when the students are directly involved in their operation instead of having them demonstrated.

8.2.2.7 Opportunities and further developments to the Horizon of 2050

It is inevitable that science will continue to evolve with wider use of remotely operated equipment, large-scale collaborations, and more computational power for big data handling. This will drive new developments in experimental physics education, involving the latest technologies and fostering skills in future professional researchers. A major challenge will be to create online experiments that are as lifelike and immersive as possible. Stereoscopic views and virtual reality headsets could offer a form of telepresence, involving direct manipulation of equipment with kinesthetic feedback. Augmented reality will be used to overlay readouts and data directly onto live views of the experiment and to operate by virtual touch or gestures. AI may be used both in the design of experiments and in data analysis. The current rate of progress suggests that at least some of these technologies will become available within the next few years. Other unexpected developments will enable us to meet new challenges as 2050 approaches.

Recent events have highlighted the strengths of remote experiments in the most dramatic fashion. During the COVID-19 pandemic, with laboratories closed and students learning online, the remote experiments described previously continued to operate, enabling students to train under lockdown conditions. As described in [30], the crisis accelerated the uptake and acceptance of remote experiments among mainstream research facilities as well as in education, with potentially lasting effects.

8.2.3 The interdisciplinary challenge: the why, the what, the where, the who, and the how

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Physics, like a large majority of other disciplines, is a limited area of teaching and research in the academic and social fields. It is itself fragmented into specialised subdisciplines representing many potential silos in the organisation of scientific knowledge, know-how, and interpersonal skills. At the same time, this partitioning between physics as a discipline in its own right, as well as between its constituent subdisciplines, is very relative insofar as the complex field of physics participates in scientific progress by cross-fertilisation with other disciplines and/or between the subdisciplines that compose it. The general trend in physics as elsewhere is to increase interdisciplinary work by interaction between disciplines [31]. These interdisciplinary openings promote scientific success and the expression of the talents of researchers who venture beyond disciplinary boundaries by making room for randomness, serendipity, and creativity in the research process [32, 33].

Why are teaching and researching done from an interdisciplinary perspective? Among the various reasons which motivate teachers and researchers to embark on the interdisciplinary path, there is agreement on the identification of four major drivers [34]: (1) the inherent complexity of physical, natural, and social phenomena; (2) the desire to explore theoretical questions and/or practical problems which are not reducible to a single disciplinary point of view; (3) the need to solve problems; and (4) the impact of the power of new technologies. Between science, technology, and society, the plural scientific field of physics and its multiple areas of application replay and combine these drivers which guide interdisciplinary work. This desire for interdisciplinary collaboration—in which physics participates with full rights and obligations—for scientific progress and the need to solve in the short, medium, and long terms the urgent problems of society (health, climate, financial, social crises, etc) does not go without disciplinary resistance, epistemological controversies, and institutional obstacles. The creation of an efficient and sustainable interdisciplinary environment should be based on a constructive dialog between disciplines and interdisciplines.

What is interdisciplinarity and in what network of concepts does it make sense? The definitions of disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary approaches express this productive tension between disciplines and their progressive decompartmentalisation (by degree) in a collaborative and integrative dynamic [35–37] (figure 8.4). If disciplinarity allows the deepening of specialized knowledge in a strictly delimited field of study, it can also be juxtaposed with other disciplinary perspectives to analyze and understand a theoretical or practical problem through different facets. This openness to multifaceted disciplinary pluralism is likely to be reconfigured in a more interdisciplinary dynamic which aims to overcome the juxtaposition of heterogeneous points of view to create interactions and links between (*inter*-, which is at the interface) the disciplines in order to

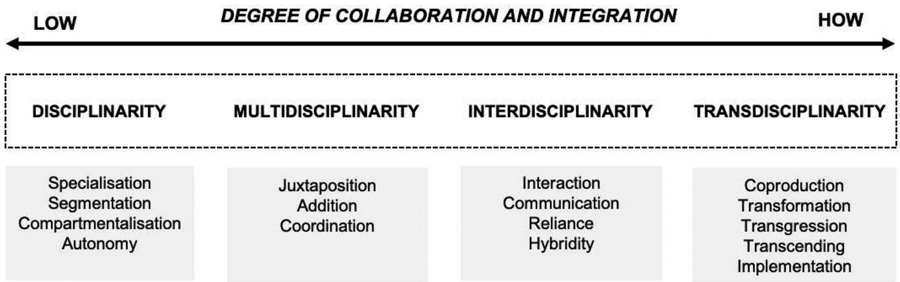

Figure 8.4. Degree of collaboration and integration between disciplines.

understand an object of study in its complexity and hybridity. Transdisciplinarity aims at the coproduction of knowledge and practical solutions between academic teachers and/or researchers and stakeholders by directly involving them from the start in the research process.

Interdisciplinarity in the broad and canonical sense is therefore:

> a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice [34].

Integration is at the heart of the interdisciplinary process which aims to bring into coherence and synthesize two or more disciplines to advance the global understanding of a theoretical or practical question and to solve complex problems. Integrative practices are also at work in transdisciplinarity, which integrates extrascientific actors in teaching and research, they transcend, transgress, and transform the borders between the academic world and the real world [38].

In what context (the 'where' of the interdisciplinary challenge) can these integrative interdisciplinary and transdisciplinary practices take place in a productive, efficient, and sustainable way? It goes without saying that universities—historically and still today structured in terms of faculties, disciplines, and subdisciplines—seem *a priori* to be places that are not very conducive to interdisciplinary work. The fact remains that academia is opening up more and more to the decompartmentalisation of disciplinary tribes and their intellectual territorialism. Positive institutional governance evolution is seen in the creation of structures dedicated to interdisciplinary and transdisciplinary collaboration which are located at the interface between several faculties and disciplines; the provision of appropriate financial, technological, and human resources; and the recognition and increased promotion of interdisciplinary networking. This new organizational culture [39] aims to develop not only at the research level, but also at the complementary levels of basic education (bachelor and master degrees) and doctoral training.

The establishment of interdisciplinary places—of third places for boundary work at the interface between disciplines and between academic and socioprofessional spheres—promotes teamwork [40] and increases the capacity to create new and original knowledge in numerous fields of research, from science and engineering to social sciences, humanities, and the arts [41]. The added value of interdisciplinary collaboration, at long distance between disciplines and not strictly between very close disciplines, can be seen in atypical combinations of knowledge from different disciplinary horizons, as shown among others by bibliometric research in citation impact term [42]. Scientific advances are thus made on a complementary double axis, aiming to balance an extension through innovation and creativity by atypical combinations of ideas, theories, and methods with pursuing the deepening of thoughts that are more in line with disciplinary paradigms. This is necessary for their recombination in new interdisciplinary fields of research.

The concrete realization of interdisciplinarity certainly requires knowing what it is, why we do it, and in what context, but it also requires teachers and researchers (the 'who' of the interdisiciplinary challenge) open to this approach and capable of developing and applying it. A spirit of openness to other disciplinary languages makes it possible to develop transversal skills, skills for dialog, and interdisciplinary and transdisciplinary communication, which facilitate the connection and integration of knowledge from at least two disciplines. The interdisciplinary teacher or researcher would therefore be the one who demonstrates in-depth knowledge in a given specialty while being able to open up and connect to a universe of knowledge extending beyond their disciplinary origin. Between disciplinary depth/verticality and transdisciplinary breadth/horizontality, the figure of the interdisciplinarian can be metaphorically embodied in a 'T-shaped person' (figure 8.5) [43]. The vertical bar of the T represents the depth of expertise in a given field, while the horizontal bar indicates the ability to collaborate with other disciplines, to import tools or other methods into one's own field of concepts, and, conversely, to export one's own tools or methods to other scientific fields. These new academic and professional profiles are being developed and gradually recognized in universities. They represent a new generation [44, 45] of teachers, researchers, and practitioners who should perhaps be able to share common values of empathy, tolerance, benevolence, and respect between disciplines, forming a common ground on which to coconstruct interdisciplinary and transdisciplinary work.

As in any scientific approach, there is no definitive recipe on the 'how' of carrying out interdisciplinary work with certainty and success. There are, however, handbooks which offer avenues for reflection and present tools, methods, and good practices (see, e.g., [46–48]), without forgetting that very often we learn from our productive mistakes [49].

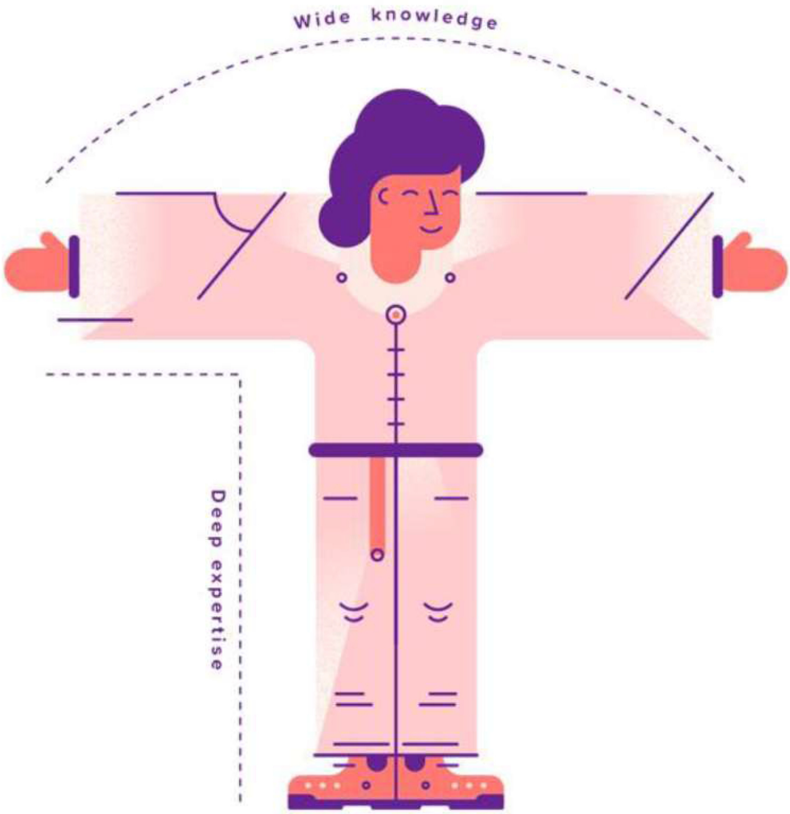

Figure 8.5. T-shaped person illustrating the relationship between wide and deep knowledge. Source: Joonas Jansson. https://dribbble.com/shots/3787357-T-Shaped-People.)

8.2.4 Education and training across sectoral borders

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The world, confronted with societal and technological challenges, is changing rapidly and dramatically, and it is moving towards an uncertain future. In an increasingly knowledge-driven society, higher education plays a major role in responding to these changes by providing the knowledge and the educated citizens necessary for prosperity and social well-being.

The societal challenges, including climate change, environmental protection, sustainable resources, energy, demographic changes, health, security, and economic competitiveness, are intertwined and complex, as shown in figure 8.6. They call for paradigm shifts and disruptive innovation. Solutions to these challenges will require convergent thinking across disciplines, creativity, and cooperation across sectoral and geographic borders.

At the education level, the goal is to shape graduates and professionals who have deep expertise in science capped by a substantial breadth of perspective, excellent collaboration and communication skills, a sound understanding of their impact, and a good sense of responsibility towards society. That means more multidisciplinary and experiential learning as well as interactive problem solving inside and outside the classroom or laboratory. Cooperation has long existed in research, and major breakthroughs have emerged often at the frontier between disciplines. The challenge now is to foster a real dialog among science, industry, policymakers, and society, which has too often been neglected before now. Universities must adapt to fulfil these new missions at the interface of education, research, and innovation and to increase the efficiency and adequacy of the system.

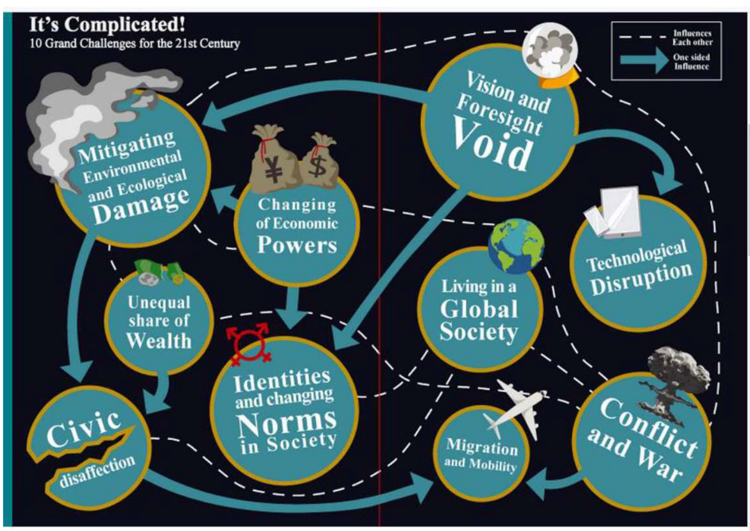

Figure 8.6. The 21st century challenges are interrelated. (Source: Ten grand challenges for the 21st century, 21st century Lab, University of Lincoln, UK, http://21stcenturylab.lincoln.ac.uk/ten-grand-challenges/.)

A possible approach in the short term is to build on solutions developed in the past 20 years, notably in the successive Framework Programmes for Research and Innovation of the European Union. For instance, EMMI, the European Multifunctional Materials Institute, is an association of academic and industry partners created on the bases of the European FP6 Network of Excellence FAME dedicated to Functional Advanced Materials and Engineering of Hybrids and Ceramics[1]. One of the objectives of EMMI is to serve as a European platform to create and conduct projects in research and education in the field of multifunctional materials science. The FAME+ Master Programme is the flagship developed within EMMI[2]. The FAME+ consortium is built with seven leading European universities in materials sciences and endorsed by seven industrial partners, seven European research and technology organisations, and 13 worldwide academic partners. Its main objective is the education of graduates with masters degrees in materials science while developing advanced skills and awareness to societal and industrial needs (see figure 8.7). Over the last 10 years, more than 200 graduates from all over the world have been awarded with the FAME+ masters degrees.

Another potential approach is exemplified by the Knowledge and Innovation Communities (KIC) catalysed by the European Institute of Technology and Innovation (EIT)[3]. Addressing economic sectors with a large potential for

1. Address Global Challenges such as Energy, Environment, Health, and Security by fostering:

- Creative thinking
- Effective use of global resources
- Increased cooperation across regions, sectors, and academic disciplines
- A cadre of well-trained global leaders
- Assembling of interdisciplinary and international teams of researchers to develop collaborative projects based on creative approaches

2. Build Global Leadership capabilities for young scientists and engineers to solve the world's most pressing problems by developing specific skills and competencies such as:

- Collaborating across sectors and disciplines
- Building global teams with complementary strengths
- Understanding the broader implications of their research
- Communicating their research to diverse stakeholders
- Understanding policy, manufacturing, and technology management
- Knowledge of international R&D infrastructures
- Interdisciplinary and intercultural communication skills

Figure 8.7. Dual Mission of the FAME+ Master Programme. (Source: https://www.fame-master.eu/brochures/.)

[1] https://www.emmi-materials.cnrs.fr/
[2] https://www.fame-master.eu/
[3] https://eit.europa.eu/

innovation and a real impact on society, the current eight KICs are partnerships that bring together businesses, research centres, and universities. Each KIC addresses a specific challenge, such as climate, food, digital, health, energy, manufacturing, raw materials and urban mobility. The main objectives are to develop innovative products and services in every imaginable area in order to create new companies and train a new generation of entrepreneurs. The training part is very important, and the EIT is strongly engaged in upgrading curricula or establishing new ones in emerging fields as well as in providing better access to research and industrial infrastructures. The creation of a forum for stakeholders (students and experts) to exchange information on education, research opportunities, and career developments is also part of the programme. Good training is very relevant for speeding up the process of technology development and the transfer of new discoveries or innovations into the marketplace.

In the KICs, each partner finances its own primary missions while all stakeholders finance together the value-added activities (mobility, skills, competencies, etc) that are developed in the frame of joint education, research, or innovation programmes. As a body of the EU, the EIT finances the KICs up to 25% of their overall resources over their typical lifetime of 15–20 years. They must be sufficiently agile and creative to become self-sustainable, generating the necessary income to finance the investments that are put in the creation of new education and research programmes. The creation of KICs should be a dynamic process, new ones being added in the future according to pressing societal and/or technological needs.

As successful as they are, the two examples above also show the limitations of the approach: These education, research, and innovation ecosystems work only at the programme and/or departmental level. The challenge of the future is to transform universities and other institutions of higher education at an institutional level in order for them to fulfil their social contract with society and adapt to a rapidly changing world [50, 51].

8.2.4.1 Conclusions

To prepare for the society of the future and improve the integration of education and research across sectoral borders, further efforts must be made today. Scientists and engineers need to become more flexible and adaptable across disciplines to be better prepared to solve societal challenges. New modes of cooperation among universities, research institutes, and industry must be developed to create a fertile ground for innovation and better address the urgent needs of society. A new paradigm in education will emerge, involving all stakeholders and relying on best practices to support decision making and new policies. Stronger computational capabilities based on AI, machine learning, and quantum computing will dominate our world, requiring more specialized and well-trained professionals across all different disciplines. Solving the actual and future societal challenges is a complex enterprise involving many interrelated parameters, as shown in figure 8.6. However, scientific and technological progress should be aligned with solid principles of governance, such as ethics, transparency, openness, participation, accountability, effectiveness, and coherence, just to name a few.

8.3 Science with and for the citizens

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Innovations that fail to take into account how people use them, copyright Katerina Kamprani.

If the physical sciences are to be successful in addressing some of the biggest problems facing humankind, it is imperative that they understand how to engage with society. This proposition is more challenging that it might appear, as there are various, and at times competing, models of how such engagement should take place. In this chapter I discuss four paradigmatic ways of governing the relationship of science and technology with society, situating each in a historical context. Starting with the ubiquitous linear model of innovation, I locate its origins and provenance and discuss how it came to be replaced, at least in part, through a 'grand challenges' paradigm of science policy and funding. I then describe how this paradigm in turn has been subjected to rigorous analytical critique by a coproduction model of science and society and how this model, in part, is being put into practice through a framework of responsible research and innovation (RRI). I conclude with reflections on how a framework of RRI can help us to navigate the grand challenges affecting the lives of citizens in the coming decades.

8.3.1 The linear model of innovation

World War II and its immediate aftermath signaled a critical moment in the unfolding relationship between science, society, and the state, especially in the United States. The Manhattan Project, involving the coordination of infrastructure and personnel in the development and production of the US nuclear programme, demonstrated the utility of science in public policy, in this case its role in helping to win the war through the detonation of two atomic bombs in Japan. In November

1944, President Roosevelt commissioned Vannevar Bush, who had had a formative role in administrating wartime military research and development through heading the US Office of Scientific Research and Development, to produce a report laying out the contributions of science to the war effort and their wider implications for future governmental funding of science. What emerged in July 1945 was the Bush report, *Science—The Endless Frontier* [52], which became the hallmark of US policy in science and technology, and the blueprint and justification for many decades of increased funding in US science.

The Bush report is associated with the linear model of innovation, postulating that the knowledge creation and application process starts with basic research, which then leads to applied research and development, culminating with production and diffusion, and associated societal benefit. Even if this sequential linkage may have been added, partially and imperfectly reflected in Bush's report [53], nevertheless it developed an iconic status as the origin and source of a dominant science policy narrative in which pure curiosity-driven science was seen as both opposed to and superior to applied science, effectively operating as the seed from which applied research grows, the economy grows, and society prospers [54]. As Sheila Jasanoff [55] has argued, the metaphor that gripped the policy imagination was the pipeline: 'With technological innovation commanding huge rewards in the marketplace, market considerations were deemed sufficient to drive science through the pipeline of research and development into commercialisation' [55]. This logic was given further impetus by the diffusion of innovation literature, notably in E M Rogers' classic text [56], which again adopted a linear and determinist model of science-based innovation diffusing into society with beneficial consequences.

Central to the post–World War II science policy narrative was the concept of the social contract, namely, that in exchange for the provision of funds, scientists, with sufficient autonomy and minimal interference, would provide authoritative and practical knowledge that would be turned into development and commercialisation. The linear model understands science and policy as two separate spheres and activities. The responsibility of scientists is first and foremost to conduct good science, typically seen as guaranteed by scientists and scientific institutions upholding and promoting the norms of communalism, universalism, disinterestness, and organised scepticism [57]. The ideal of science was represented as 'the Republic of Science' [58], separate from society, and as a privileged site of knowledge production. The cardinal responsibility of science, according to this model, is primarily to safeguard the integrity and autonomy of science, not least through practices of peer review as the mechanism that guarantees the authority of science in making authoritative claims to truth, thus ensuring its separation from the sphere of policy and politics.

This division of powers served the interests of both actors. For scientists, it meant a steady and often growing income stream as well as considerable autonomy; for politicians and policymakers, it provided a narrative that enabled them to claim that their policies were grounded in hard, objective evidence and not in subjective values or ideology. This division was also written into institutional arrangements for science policy. The Haldane Principle, for instance, by which the decision-making powers about what and how to spend research funds should be made by researchers rather than politicians, was written into national science funding bodies in the UK as far back as 1918, operating especially following World War II as a powerful narrative for self-regulation and for safeguarding the autonomy of science.

So far, we have described the linear model of science and technology, the assumptions that underpin its governance, including its optimistic and deterministic view of the relationship between pure science and social progress. However, as the 20th century progressed, this model came increasingly to be under strain as providing robust governance in the face of real-world harms that derived from scientific and technological innovation. Whereas the traditional notion of responsibility in science was that of safeguarding scientific integrity, responsibility in scientific governance came to include responsibility for impacts that were later found to be harmful to human health or the environment. The initial governance response was to acknowledge that science and technology could generate harms but that these could be evaluated in advance and within the bounds of scientific rationality through practices of risk assessment. Following a report from the US National Research Council [58], systematising the process of risk assessment for government agencies through the adoption of a formalised analytical framework, a rigorous and linear scheme was promoted and disseminated in which each step was based on available scientific evidence and in advance of the development of policy options. Risk assessment was thus a response to the problems of the linear model but was still very much within the linear model's framing and worldview.

Notwithstanding the efficacy of risk assessment to mitigate the harms associated with science and technology, notably in relation to chemicals and instances of pollution, it did little to anticipate or mitigate a number of high-profile technology disasters that took place throughout the latter half of the 20th century. Those disasters demonstrated that science and technology can produce large-scale effects that evaded the technical calculus of science-based risk assessment [59]. High-profile disasters included the accident at the Three Mile Island nuclear power plant in the US in 1979; the toxic gas disaster at the Union Carbide pesticide plant in Bhopal, India, in 1984; the disaster at the Chernobyl nuclear power plant in Ukraine in 1986; the controversy over bovine spongiform encephalopathy (BSE), also known as 'mad cow disease,' in the UK and Europe throughout the late 1980s and 1990s; and the controversy over genetically modified food and crops in the 1990s and 2000s first in Europe and then across much of the Global South. The nuclear issue was a focal point throughout the 1970s and 1980s as a result of wider concerns about technological modernity, manifested in large social movements that mobilised against the potential of science-led innovation to produce cumulative unknown and potentially cataclysmic risks. This was theorised most famously by the sociologist Ulrich Beck. Through his notion that modernity had entered a new phase, dubbed *the risk society*, science and technology were seen as having produced a new set of global risks that were unlimited in time and space, manufactured, potentially irreversible, incalculable, uninsurable, difficult or impossible to attribute, and dependent on expert systems and institutions for their governance. In this view, society operates as an experiment in determining outcomes [60].

The saga of BSE in the UK and Europe illustrates one such risk that was woefully and inadequately governed by a reliance on formal processes of science-based risk assessment, where the political controversy derived from the inadequate handling of a new disease in cattle under conditions of scientific uncertainty and ignorance, in the context of Britain's laissez-faire political culture. In this case, despite reassurances from government ministers, who claimed to be innocently following scientific advice that a transmission across the species barrier would be highly unlikely, a deadly degenerative brain disease spread from cattle to humans, escalating to such proportions as to threaten the cohesion of the EU [61].

More generally, risk assessment as a formal mechanism of scientific governance came under sustained criticism [62]. First, it embodies a tacit presumption in favour of change in assuming that innovations should be accepted in the absence of demonstrable harm. Second, it prioritises short-term safety considerations over long-term, cumulative, and systemic impacts, including those on the environment and quality of life. Third, it prioritises *a priori* assumptions of economic benefits with limited space for public deliberation of those benefits and their effects on society. Fourth, it restricts the range of expertise that is considered to be scientific expertise, typically from a restricted set of disciplines, with limited scope to access the knowledge of ordinary citizens. Fifth, it ignores the values and deep-seated cultural presuppositions that underpin how risks are framed, including the legitimacy of alternative framings.

8.3.2 The grand challenge model of science for society

While the linear model has been criticised for failing to account for the risks associated with late modernity, the model has also come under sustained criticism as offering an inadequate account of how the innovation system is structured and for what ends. Throughout the latter part of the 20th century, science and innovation became increasingly integrated and intertwined. The knowledge production system moved from the rarefied sphere of elite universities, government institutes, and industry labs into new sites and places that now included think tanks, interdisciplinary research centres, spinoff companies, and consultancies. Knowledge itself became less disciplinary based and more bound by context and practical application. Traditional forms of quality control based on peer-based systems became expanded to include new voices and actors, adding additional criteria related to the societal and economic impact of research. Variously framed using new intellectual concepts that included 'mode 2 knowledge' [63], 'post normal science' [64], 'strategic science' [65], and the 'triple helix' [66], a new model of knowledge production emerged in which science came to be represented as the production of socially robust or relevant knowledge, alongside, and often in conflict with, its traditional representation as knowledge for its own sake. Interestingly, in a later book, some of the same authors contextualised this transformation to accounts of societal change, particularly the Risk Society and the Knowledge Society, where 'society now speaks back to science' [67, 68].

One institutional response to critiques of the linear model has been the development of initiatives aimed at ensuring that science priorities and agenda-setting processes respond to the key societal challenges of today and tomorrow. The grand challenge approach to science funding best illustrates this approach. Historical examples of grand challenges range from the prize offered by the British Parliament for the calculation of longitude in 1714 to President Kennedy's challenge in the 1960s of landing a man on the Moon and returning him safely to the Earth. However, it was in the 2000s that the concept developed into a central organising trope in science policy, propelled *inter alia* by the Gates Foundation as a way of mobilising the international community of scientists to work towards predefined global goals [69]. In European science policy, the Lund Declaration in 2009 was a critical moment, which emphasised that European science and technology must seek sustainable solutions in areas such as global warming, energy, water and food, ageing societies, public health, pandemics, and security.

More generally, the concept has been embedded across a wide array of funding initiatives. Most recently, the European Commission (EC) instituted the Framework 8 Horizon 2020 programme, in which €80 billion of funding was to be available over the 7 years from 2014 to 2020, as a challenge-based approach that reflected both the policy priorities of the EU and the public concerns of European citizens. It was legitimated as responding to normative targets enshrined in treaty agreements; these included goals regarding health and well-being, food security, energy, climate change, inclusive societies, and security. In other words, it was based on the assumption that science does not necessarily, when left to its own self-regulating logic and processes, respond to the challenges that we, as a society, collectively face. Some degree of steering or shaping on the part of science policy institutions is needed to ensure alignment. It is thus embedded in a discourse about the goals, outcomes, and ends of research.

Over the last decade, the grand challenge concept has become deeply embedded in science policy institutions as a central and organising concept that appeals to national and international funding bodies, philanthropic trusts, public and private think tanks, and universities alike. It operates not only as an organising device for research calls but also as a way of organising research in research-conducting organisations, notably universities. For example, my university, Wageningen University, configures its core mission and responsibility in strategic documents as producing 'science for impact', principally through responding to global societal challenges of food security and a healthy living environment [70].

The grand challenge concept is clearly aligned with the 'impact' agenda, in which researchers increasingly must demonstrate impact in research-funding applications and evaluation exercises. These concepts help to reconfigure the social contract for science such that, at least in part, the responsibility of science is to respond to the world's most pressing societal problems, while the responsibility of science policy institutions is to ensure that the best minds are working on the world's most pressing problems [69]. Perhaps not surprisingly, these initiatives have proved to be controversial within the scientific community, as, for example, was shown by backlash from the scientific community to an initiative from one of the UK research councils, the Engineering and Physical Science Research Council (EPSRC), to prioritise its funding for grants, studentships, and fellowships according to national importance criteria [71].

More recently, scholars in the field of science and technology have added a further analytical layer [72]. They analysed the concept of the grand challenge scientist and the ways in which this has replaced the concept of the scientist that was prevalent in the linear model of innovation. Since at least Vannevar Bush's report *The Endless Frontier* (1944) [52], the dominant figure of the scientist was that of a lone individual discovering the frontiers of knowledge through pioneering or frontier research at the rock face of knowledge. However, while the ideal type of this kind of scientist was one who practised 'the risk taking behavior of rugged competitive individualists pioneering into the unknown' [72], the grand challenge concept configured a different kind of scientist. The grand challenge scientific endeavour still remains competitive but now has become collective, even sports-like, in the ways in which teams are presented as fighting to achieve a significant long-term goal, the accomplishment of which will have significant societal impacts. This tends to favour the organisation of science in highly interdisciplinary and collaborative units, as has become the case in systems biology and synthetic biology. Yet even though grand challenges are attempts to respond to society and to the public interest, the choice and framing of the challenges themselves have tended to remain those that have been chosen top-down by funding organisations [73] and in ways that often lend themselves to 'silver bullet' technological solutions [69]. Nevertheless, the grand challenge concept can be seen as part of an attempt to establish a new social contract for the public funding of science and as an important counterweight to the other dynamic that has affected the autonomy of science: the relentless influence of economic drivers that has come to dominate research policy agendas [74].

8.3.3 The coproduction model of science and society

If the grand challenge science policy model seeks to reconfigure the social contract of science such that its core value lies not with the pursuit of pure knowledge but in providing solutions to the world's most pressing problems, the coproduction model and approach seek to reconfigure the social contract in another direction. While the linear model views science as the motor of societal progress and the grand challenge model views science as the provider of solutions for society, the model of coproduction views the spheres of science and social order as mutually constitutive of each other.

Developed by Sheila Jasanoff and colleagues and building on decades of scholarship in science and technology studies (STS), the coproduction concept criticises the idea of science as producing incontrovertible fact. AAccording to Jasanoff and Simmet, 'Facts that are designed to persuade publics are coproduced along with the forms of politics that people desire and practice' [75]. This takes place in deciding which facts to focus on, in identifying whose interests the facts are used to support, and in observing that public facts are achievements, or what Jasanoff and Simmet call 'precious collective commodities, arrived at … through painstaking deliberation on values and slow sifting of alternative interpretations based on relevant observations and arguments' [75].

There are three broad implications that derive from this approach. First, if the authority and durability of public facts depend not on their status as indelible truths, but on the virtues and values that have been built into the ethos of science over time, it follows that we need to give special attention precisely to these virtues and to how they have been cultivated over time by institutional practice as an important constituent of democratic governance. As Jasanoff and Simmet claim, 'building strong truth regimes requires equal attention to the building of institutions and norms' [75].

Second, if science and social order are coproduced, then it becomes incumbent on the research enterprise to examine precisely the relationship in practice between scientific knowledge production and social order as evinced in particular sites. Variously studying in depth the operation of scientific advisory bodies, technical risk assessments, public inquiries, legal processes, and public controversies, STS scholars have identified both the values out of which science is conducted, including the interests it serves, and the ways in which these configurations can, over time, contribute to the formation of new meanings of life, citizenship, and politics, or what more generally can be dubbed 'social ordering' (see, among many others, [76–80]).

Third, if it is acknowledged that science and social order are coproduced, even if unwittingly through forms of practice, the question arises as to what values underpin the scientific knowledge production system and the extent to which these align with broader societal values. Indeed, to what extent have the values and priorities that are tacitly embedded in scientific innovation been subjected to democratic negotiation and reflection? Perhaps more worryingly, to what extent do dominant scientific values reflect those of incumbent interests that may be, perhaps unwittingly, closing possibilities for different scientific pathways linked to alternative visions of the social good [81, 82]. Responding to these questions, a line of research has emerged since the late 1990s, particularly prevalent in northern parts of Europe, aimed at early-stage public and societal participation in technoscientific processes as a means of fostering democratic processes in the development of, approach to, and use of science and technology. Such initiatives, funded both by national funding bodies and by international bodies, such as the EC, are typically aimed at improving relations between science and society and restoring legitimacy [83]. In practice, they have been developed for reasons that include the belief that they will help restore public trust in science, avoid future controversy, lead to socially robust innovation policy, and render scientific culture and praxis more socially accountable and reflexive [84, 85]. Initiatives aimed at public engagement in science have become a mainstay in the development of potentially controversial technology, notably in the new genetics, and have even been institutionally embedded into the machinery of government in initiatives that include the UK Sciencewise programme dialogs on science and technology [86]. In academia, they have contributed to institutional initiatives that include Harvard University's Science and Democracy Network and to the subdiscipline of public engagement studies [87].

8.3.4 A framework of responsible research and innovation

RRI concept represents the most recent attempt to bridge the science and society divide in science policy. Promoted actively by the EC as a cross-cutting issue in its

Horizon 2020 funding scheme (2014–20), and embedded in its subprogramme titled Science with and for Society, RRI emerged as a concept that was designed both to address European (grand) societal challenges and to 'make science more attractive, raise the appetite of society for innovation, and open up research and innovation activities; allowing all societal actors to work together during the whole research and innovation process in order to better align both the process and its outcomes with the values, needs and expectations of European society' [88]. To some extent RRI has been an umbrella term and is operationalised through projects aimed at developing progress in traditional domains of EC activity, nominally in the so-called five keys of gender, ethics, open science, education to science, and the engagement of citizens and civil society in research and innovation activities (Rip 2016). In this interpretation, RRI is a continuation of initiatives aimed at bringing society into EU research policy, starting with its Framework 6 programme (2002–6) titled Science and Society and its follow-on Framework 7 programme (2007–13) titled Science in Society. It has been identified as a top-down construct, introduced by policymakers and not by the research field itself [89], standing 'far from the real identity work of scientists' [72].

Another articulation of the RRI concept is also available. Alongside colleagues Richard Owen and Jack Stilgoe, I have been involved in developing a framework of responsible innovation for the UK research councils. Our intention at the time was to develop a framework out of at least three decades of research in STS, building on the coproduction model as articulated earlier in this section. Our starting point drew on the observation that from the mid-20th century onwards, as the power of science and technology to produce both benefit and harm became clearer, it had become apparent that debates concerning responsibility in science need to be broadened to extend both to their collective and to their external impacts on society. This follows directly from the coproduction model as articulated previously.

Responsibility in science governance has historically been concerned with the 'products' of science and innovation, particularly impacts that are later found to be unacceptable or harmful to society or the environment. Recognition of the limitations of governance by market choice has led to the progressive introduction of post hoc and often risk-based regulation, such as in the regulation of chemicals, nuclear power, and genetically modified organisms. This has created a well-established division of labour in which science-based regulation, framed as accountability or liability, determines the limits or boundaries of innovation and the articulation of socially desirable objectives—or what Rene von Schomberg describes as the 'right impacts' of science and innovation—is delegated to the market [90]. For example, with genetically modified foods, the regulatory framework is concerned with an assessment of potential risks to human health and the environment rather than with whether this is the model of agriculture we collectively desire.

This consequentialist and risk-based framing of responsibility is limited, because the past and present do not provide a reasonable guide to the future and because such a framework has little to offer to the social shaping of science towards socially desired futures [91, 92]. With innovation, we face a dilemma of control [93] in that we lack the evidence that can be used to govern technologies before pathologies of path dependency, technological lock-in, entrenchment, and closure set in.

Dissatisfaction with a governance framework that is dependent on risk-based regulation and with the market as the core mediator has moved attention away from accountability, liability, and evidence towards more future-oriented dimensions of responsibility—encapsulated by concepts of care and responsiveness—that offer greater potential for reflection on uncertainties, purposes, and values and for the cocreation of responsible futures.

Such a move is challenging for at least three reasons: first, because there exist few rules or guidelines to define how science and technology should be governed in relation to forward-looking and socially desirable objectives [94]; second, because the implications of science and technology are commonly a product of complex and coupled systems of innovation that rarely can be attributed to the characteristics of individual scientists [60]; and third, because of a still-pervasive division of labour in which scientists are held responsible for the integrity of scientific knowledge and in which society is held responsible for future impacts [95].

It is this broad context that guided our attempt to develop a framework of responsible innovation for the UK research councils [96, 97]. Building on insights and an emerging literature largely drawn from STS, we started by offering a broad definition of responsible innovation, derived from the prospective notion of responsibility described previously:

> Responsible innovation means taking care of the future through collective stewardship of science and innovation in the present [96].

Our framework originates from a set of questions that public groups typically ask of scientists. Based on a meta-analysis of cross-cutting public concerns articulated in UK government-sponsored public dialogs on science and technology, we identified five broad thematic concerns that structured public responses. These were concerns with the purposes of emerging technology, with the trustworthiness of those involved, with whether people feel a sense of inclusion and agency, with the speed and direction of innovation, and with equity, that is, whether the technology would produce fair distribution of social benefit [86]. This typology, which appears to be broadly reflective of public concerns across a decade or so of research and across diverse domains of emerging technology (including our own, [98–102]), can be seen as a general approximation of the factors that mediate concern and that surface in fairly predictable ways when people discuss the social and ethical aspects of an emerging technology. If we take these questions to represent aspects of societal concern about research and innovation, responsible innovation can be seen as a way of embedding deliberation about these issues within the innovation process. From this typology we derived four dimensions of responsible innovation—anticipation, inclusion, reflexivity, and responsiveness—that provide a framework for raising, discussing, and responding to such questions. The dimensions are important characteristics of a more responsible vision of innovation, which can, we argue, be heuristically helpful for decision making on how to shape science and technology in line with societal values.

Anticipation is our first dimension. Anticipation prompts researchers and organisations to develop capacities to ask 'what if…?' questions, to consider contingency, what is known, what is likely, and what are possible and plausible impacts. Inclusion is the second dimension, associated with the historical decline in the authority of expert, top-down policymaking and the deliberative inclusion of new voices in the governance of science and technology. Reflexivity, the third dimension, is defined, at the level of institutional practice, as holding a mirror up to one's own activities, commitments, and assumptions; being aware of the limits of knowledge; and being mindful that a particular framing of an issue may not be universally held. Responsiveness is the fourth dimension, requiring science policy institutions to develop capacities to focus questioning on the three other dimensions and to change shape or direction in response to them. This demands openness and leadership within policy cultures of science and innovation such that social agency in technological decision making is empowered.

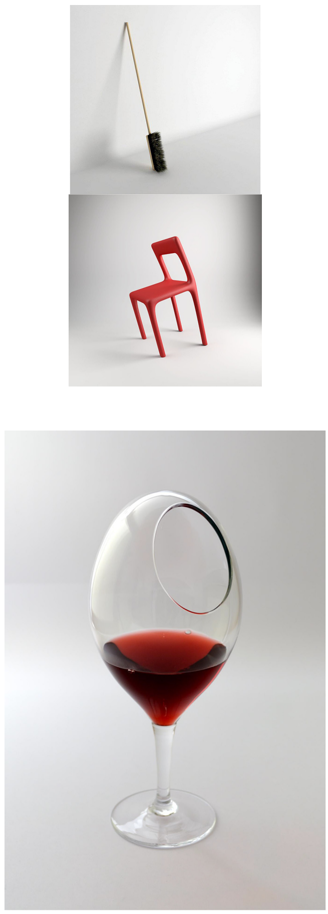
To summarise, our framework for responsible innovation starts with a prospective model of responsibility, works through four dimensions, and makes explicit the need to connect with cultures and practices of science and innovation. Since its inception our framework has been put to use by researchers, research funders, and research organisations. Indeed, since we developed the framework in 2012, one of the UK research councils, the EPSRC, has made an explicit policy commitment to it [103, 104]. Starting in 2013, using the alternative 'anticipate-reflect-engage-act' (AREA) formulation [105], EPSRC has developed policies that set out its commitment to developing and promoting responsible innovation and its expectations both for the researchers it funds and for its research organisations.

8.3.5 Challenges and opportunities

In this section I have discussed four paradigmatic ways of governing the relationship of science and technology with society. I began with the linear model, in which science is represented as the motor of prosperity and social progress and in which the social contract for science is configured as that of the state and industry providing funds for science in exchange for reliable knowledge and assurances of self-governed integrity. I then explored the dynamics and features which contributed to a new social contract for science in which the organisation and governance of science became explicitly oriented towards the avoidance of harms and the meeting of predefined societal goals and so-called grand challenges. A coproduction model of science and society was subsequently introduced to provide a better understanding of how science and social order are mutually constitutive and of the implications of such an approach for science and democratic governance. Finally, I set out a framework of responsible innovation as an integrated model of aligning science with and for society.

These four models should not be seen as wholly distinct or unrelated. Typically, they operate in concert, sometimes harmoniously, other times less so, in any governance process. Nevertheless, the broad move beyond the linear model of science and society must be applauded, both because science devoid of societal shaping is clearly poorly equipped to respond to the societal challenges we collectively face and because the premises that underpin the linear model, such as the fact–value distinction, are clearly poorly aligned with contemporary intellectual debate.

The world of 2050 is likely to be very different from that of today. Advances in science and technology are likely to present all kinds of challenges—as well as opportunities—at various scales and temporalities. Advances in digital technologies, AI, machine learning, nanotechnology, robotics, gene editing, synthetic biology, and quantum mechanics are undoubtedly going to have transformative impacts on everyday life, for good and ill. Not only will we need such advances to help tackle some of the profound challenges of today and tomorrow, ranging from climate change to global pandemics, food security, and healthy soils and oceans, but we need to engage citizens in partnership with science in the coproduction of solutions. A framework of RRI offers opportunities, tools, and possibilities to make science and its governance more responsive to the grand challenges of the 21st century by helping to ensure that the formulation of responses is aligned to the question as to what kind of society we want to be [106].



More useless innovations, copyright Katerina Kamprani.

8.4 Open communication and responsible citizens

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8.4.1 Open communication: public engagement with science

We live in challenging times, and the future lies in our hands. How is it possible for humankind to follow its basic need to expand horizons and gather knowledge while maintaining responsibility for a sustainable future? We believe that one of the key elements of responsible research is not only keeping best practices, but also making the past achievements of humankind accessible to future generations.

'Scientists keep an open line of communication with the public[4]' [107]; this call for action from the editor of *Nature Medicine* in October 2020 came at a time when our society was struggling with a global pandemic, experiencing fights for social justice, and suffering from the climate crisis. Scientists need to openly communicate with the public and engage fellow citizens with research activities. Public engagement with science is no longer a 'nice-to-have' activity but a 'must-have' one.

'Science communication', 'public engagement', and 'education and public outreach' are blanket terms covering any related topics, from goals to methodology. These terms describe the many ways in which the scientific community can share its research activities and their benefits with society. B Lewenstein [108] categorizes public engagement in two main aspects: as a learning activity and as a public participation in science (table 8.2). Both have in common that scientists and science educators reach out to individuals and society at large with various programs. Engagement is a two-way communication process, involving listening and interaction for mutual benefit. Public engagement is also an essential tool to build and strengthen public support for research. Indeed, the trend for evidence-based public policy increasingly relies on access to a wide variety of specialists, many based in universities or research facilities.

8.4.1.1 Developments in public engagement

Historically, science communication has gone through three main phases: science literacy (also known as the deficit model), public understanding of science, and, recently, public engagement of science and technology. These phases have moved forward because of several policy reports.

In 1985, the Royal Society identified a systematic lack of interest and literacy in science. The result can be imagined as a trench gaping between the science domain

[4] We use the term public as an umbrella term for non-university audiences, including fellow citizens, education stakeholders and policymakers.

Table 8.2. Overview of the main categories of public engagement initiatives based on [109].

Category	Characteristics	Examples
Developing an interest in science	Experience excitement, interest, and motivation to learn about science	• Exhibits (e.g.: CERN's Universe of Particles [110]) • Media: TV news, newspapers, magazines, etc • Social media
Understanding (some) science	• Understand concepts, explanations, arguments, models, and facts related to science • Manipulate, test, explore, predict, question, observe, and make sense of science	• Public talks (e.g. Physics Matters Lecture Series [111]) • Documentaries (e.g., BBC's 'The Secrets of Quantum Physics' [112]) • Popular science books and magazines (e.g., Stephen Hawking's seminal book *A Brief History of Time* [113]) • Workshops and hands-on exhibitions • Public websites
Using scientific reasoning and reflecting on science	Reflect on science as a way of knowing; on processes, concepts, and institutions of science; and on their own process of learning about phenomena	• Community and dialog initiatives (e.g., Quantum Delta Living Lab [114])
Participating in the science enterprise	Public participates in scientific activities and learning practices with others, using scientific language and tools Public identifies as people who know about, use, and sometimes contribute to science	• Citizen science projects (e.g., Steelpan Vibrations [115])

and society (figure 8.8). Science communication ought to be key to bridge that trench. The initial top-down or one-way strategy for communicating to the public, however, has resulted in 'very little improvement in adult scientific literacy' [116]. Improvement was expected when the UK's House of Lords Science and Society report spearheaded the public engagement model. Recently, science has progressively advanced into various areas of society [117]. As Schäfer notes, while scientists and journalists had attempted to increase citizens' science literacy by popularizing science, several events of global reach made the public more aware of the societal impact of science. A two-way street as communication strategy turned out to be better (see figure 8.8). A direct dialog with the public is essential not only for

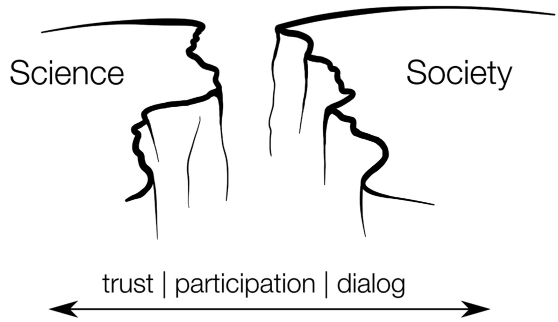

Figure 8.8. Illustration of the trench between science and society and the latest efforts to bridge that trench with a two-way communication strategy.

democratic participation in research [118], but also to facilitate more trust and confidence in science [119]. In addition, new trends in crowd-sourcing have emerged in science: notably, citizen science projects with crowd-based data collection and analysis or crowd-funding platforms [120].

Despite these efforts in pushing for more public engagement, the Public Attitudes to Science report of 2019 [121] documented an evident gap between citizens and science. While 51% of respondents felt too little exposed to science, 69% of them agreed that 'scientists should listen more to what ordinary people think'. This gap has been starting to shrink, thanks also to the increasing significance of science communication. The report moreover states that citizens have developed more positive attitudes towards science and more trust in science. They feel better informed, and science seems more accessible (see section 8.4.1.2). It is, however, worrisome that only a minority of respondents considered science important and useful in everyday life.

8.4.1.2 Open science and public engagement

Public engagement is an endeavor that takes many forms, ranging from education programmes to citize -science projects and science festivals. All of these help researchers to disseminate the societal benefits of their work while keeping abreast of public concerns and expectations. Public engagement activities provide a platform for researchers to discuss their projects and objectives with the wider public. For optimal benefits these actions must be practical, innovative, research-based, and educational, feeding each other with ideas, opportunities for research studies, and even financial resources [122].

Public engagement helps to maximize the flow of knowledge and cooperation between research communities and society, giving researchers the potential to create an impact through learning and innovation [123]. Strategic investment in public engagement helps to maximize this potential by focusing attention and support on how research enriches the lives of people. It also contributes to social inclusion and social responsibility and allows researchers to better respond to local and global social issues [124] with appropriate effective support to people [125]. Building trust and mutual understanding is critical to a healthy higher education and research system [126, 127], especially at a time when deference to authority and professional expertise is decreasing.

The Internet has fostered many citizen science projects in which the public gets involved in data collection, analysis, or reporting. The low-level access to the scientific process is one key advantage of such projects, and the large collaborations that are generated allow widespread research, leading to discoveries that single scientists could hardly achieve on their own [128].

When it comes to higher education and science communication, a study by the Wellcome Trust [129] shows a positive trend with regard to researchers but with clear caveats. For example, is the science communication activity always as effective as it could be? Examples stated in the report are low frequencies of engagement and a clear bias in target audiences. According to [130], there has been a lack of a coherent push for science communication in the academic system. There are also discussions in the scientific community about whether or not public engagement can harm the researcher's scientific career—also known as the Carl Sagan effect [131, 132]—alongside negative opinions. On the other hand, it is emphasized that communicating with the public can boost academic performances [131, 132]. However, new policies are needed to promote public engagement.

The good news is that science communication is today an established subject at many universities with an increasing number of options in the various curricula up to the PhD level. Its interdisciplinary and multidisciplinary nature is a 'sign of the subject's vitality, but it is also a condition of its vulnerability' [133]. Indeed, it is challenging for science communication to become a recognized teaching field when it is positioned between and across faculties and disciplines.

We believe that the academic institutions need to provide long-term support to retain the necessary skills, experience, and resources to facilitate communication efforts. This should not add to the existing pressure for publishing and being competitive but should be part of the job profile of responsible scientists [134]. We argue that to avoid a trench to form between scientists and communicators, research institutions should not rely on institutionalized science communication.

We do, however, endorse open and public spaces where innovative science communication can take place. Such 'Idea Colliders' [135] have the chance to supersede traditional science museums and promote critical scientific thinking and decision making. These spaces can trigger debates in an interdisciplinary setting involving scientists and citizens from diverse disciplines, including those from the cultural and political sectors. Design is one example of a largely interdisciplinary interface, able to facilitate communication between science and society and thus to contribute to novel and transformative narratives [136].

In terms of science communication research, as an increasingly academic discipline, theoretical and applied research in science communication attracts scientists from various backgrounds, such as the history of science, media studies, psychology, and sociology. In-depth knowledge in science communication is essential for the other core areas of public engagement activity described previously. 'Science is not finished until it is communicated,' said UK Chief scientist Sir Mark

Walport in 2013. These words reflect the urgent need for the science enterprise to fully commit to public engagement and place societal impact at the core of its research.

8.4.1.3 Responsible research and innovation

RRI is a policy principle [137] based on societal aspects of research, such as public engagement, research integrity, and ethics. It focuses on aligning research and innovation processes and outcomes with the values and needs of the greater society. It is the responsibility of individual researchers and innovators to consider these principles in their daily work and to anticipate the societal consequences of their practice. The six main dimensions of RRI are research engagement with society, gender equality, open access, science education, ethics, and governance in research and innovation. This policy further demands the following transdisciplinary approaches to modern research:

- Collaboration of societal actors (researchers, citizens, policymakers, business, third sector organisations, etc) during the whole research and innovation process so to better align with societal values and expectations.
- Enabling easier access to scientific results, including open science and public engagement.
- Uptake of gender equality and ethics in the whole process. Scientific curiosity should try to answer not only the question 'can we' (scientific or technical feasibility) but also the question 'should we' (societal acceptance).
- Formal and informal science education.

Current research policies such as RRI demand wider participation of researchers in societal issues. For example, the OECD [138] and the EU [139] have published specific societal impact frameworks for research communities and facilities. Research facilities such as ESO [140] and CERN [141] have also published reports on their societal impact. However, in general, there is still a mismatch between policy expectations and relevant scientific engagement.

8.4.1.4 Future challenges

We find ourselves in challenging times. Modern challenges are complex, broad, global, and deeply rooted in societal dimensions. The climate crisis and the COVID-19 pandemic are just symptoms but with connected causes. Our roles and responsibilities as scientists are changing at the same speed as that at which the environment changes—an environment that we have described and tried to understand for decades. The knowledge we gained in that process should help lead to fast progress in preserving our environment (or nature) but can no longer remain the exclusive property of specialized research fields. Open communication among scientists, across disciplines, and with society (public engagement) is crucial on our way towards the Horizon of 2050. While these communication efforts are key to meeting global challenges, their success depends on a well-functioning science–society relationship, which is a difficult task in a world that is rather unstable politically, socially, and economically.

8.4.1.5 Global environmental challenges

Global challenges and risks have developed together with globalization. The 2018 Global Compact on Refugees, the IPCC 6th assessment report [142], and the Global Risks Report (2020) demonstrate that it is imperative to prepare for a sustainable future. Ironically, this seems the greatest challenge to society itself [126]. Sciences comprise disciplines that seek to describe nature [143] with an understanding and analysis of complex phenomena concerning the bigger picture [144]. Science therefore helps in developing the knowledge to assess global challenges and risks. It requires also large-scale collaborative efforts to encompass the complexity of global and interconnected phenomena such as the climate crisis. The status of expertise has changed considerably from being exclusive to being broadly available and often challenged by society itself [145]. The climate crisis, for example, is no longer of interest only for scientific studies. As it implies huge risks for humanity, it puts extra pressure on all disciplines to provide the public with reliable knowledge [126] and guidelines over the upcoming decades. Scientific evidence concludes that the changing world climate will affect our everyday life in the future [142] and that swift action is required [146]. Meanwhile, citizens depend on accurate risk assessment (Global Risks Report, World Economic Forum, 2020 [147]), as evidenced by the COVID-19 pandemic and the climate crisis appearing as correlated symptoms [148–150]. Interdisciplinary research is key in tackling these grand challenges to society.

8.4.1.6 Society's need for public engagement in the face of global challenges

Considering these extensive and complex challenges that society will face in the upcoming decades, the public demands dedicated support by scientists, science communicators, and science journalists beyond solely increasing their scientific knowledge. Engaging the public with the process and method of science promotes a more comprehensive understanding, improves the relationship between science and society [127], helps citizens to appreciate the complexity of current and future challenges, and builds trust in scientists [126, 145].

The situation is still worrisome. Although 64% of Americans are at least 'somewhat worried' about global warming, only 22% actually understand how strong the level of scientific consensus is on global warming, according to a 2021 survey by the Yale Program on Climate Change Communication. The gap between science and the understanding of science by the public is fueling a lack of trust in science, feelings of uncertainty, and social inertia [151]. Worse, it gives sceptics and deniers a lot of momentum. As physicists, we have the privilege of understanding and being able to evaluate risks. This gives us the responsibility to share our knowledge with the citizens who are often left alone in assessing such risks and making decisions on issues such as extreme weather incidences [152, 153]. Public controversies arising over various scientific and technical issues [154] have luckily boosted numerous efforts in science communication across disciplines [155]. Now and in the coming years, we need to acknowledge that the path towards a sustainable future on our planet is a systemic transformative process involving the entire society worldwide.

Interdisciplinary research (in physics) and the emerging field of the science of science communication have developed at a fast pace in recent years (e.g., [156, 157]). They have not yet reached the speed at which our society must respond to accelerated socioeconomic and Earth systems–related trends [149] with sustainable solutions. Swift action is imperative for all of us to bridge the remaining gap between the sciences and society over the coming decades (see figure 8.11). In summary, present times demand for a culture in society that does the following:

- Appreciates [158] and trusts [126] science.
- Understands the scientific process as a probabilistic approach [159] and the concept of uncertainty in the interpretation of scientific results [156], differentiates between scientific uncertainties and low-quality or doubtful science [160], and disregards the negative connotations of the term ‘uncertainty’ [161].
- Makes scientifically motivated decisions.
- Seeks a dialog with society ([156] and references therein).

Moreover, the role of politics must not be forgotten, as science communication guarantees the ‘democratic legitimacy of funding, governance and application of science’ [162].

We encourage our colleagues in all fields of physics to appreciate the increasing challenging needs of our society, scientists included, and to engage in the exciting communication landscape.

8.4.1.7 Challenges and opportunities in modern approaches of science communication

The research community and citizens are both challenged by modern science communication [145], and tension has been growing between experts and the public in recent years. How can experts become more valued and respected? How can citizens identify true experts and factual knowledge in the complex web of the ’infodemic’? The ‘overabundance of (also wrong) information’ can ‘undermine the public health response’ and fuel conspiracy theories, pseudoscientific content, or large-scale ‘controversies over scientific and technical issues’ [154]. Typical examples are related to COVID-19 [163]; the misinterpretation of scientific knowledge in the documentary ‘Cowspiracy’ [164], in particular regarding the ‘Global Warming Potential’ (GWP) cited in the 6th IPCC report [142]; and the apparent but rebounding drop in CO_2 emissions induced by the measures that were initially taken against the spread of COVID-19 [165]. Some authors have investigated the complex diversity of how bloggers and contrarian bloggers discuss topics of public interest [166], such as the scientific consensus behind the climate crisis. Clearly, it requires specific training and expertise to (1) filter reliable knowledge in the face of complex and global crises, where opposing expert opinions are pervasive on the Internet [167], (2) manage the challenges of the ‘mediatisation’ of complex information and discussions [168–170], (3) avoid being diverted from biases (e.g., cognitive, self-confirmation, or anchoring), and (4) make scientifically driven decisions in everyday life [171].

Despite the tragic developments of the COVID-19 pandemic, it has also provided opportunities for researchers to 'rethink the role they want to play in society at large' [107]. For the first time, our society experienced the consequences of a global crisis that affects the lives of most of the world population at short time scales. The climate crisis, however, despite its evidently fatal consequences for humankind, is still largely perceived as an abstract issue given the longer time scales involved in climate variability [172, 173]. Sociologist Kate O'Brien argues that the pandemic has shown that society is in fact able to adapt and that a major global transformation in response to the climate crisis is possible [174, 175].

Science communication practices have proven capable of bridging science and society during the pandemic and hence contribute to a global transformation process [176, 177].

8.5 Science and ethics

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8.5.1 Introduction

The phrase 'science and ethics' generates more than 20 million hits by the search engine Google, illustrating the significance of this topic. There are several reasons for this interest, one being the public understanding of the fundamental impact of science and of its applications. The increased pressure on scientists to demonstrate skills and productivity to build their careers and secure financing for their research may have tempted them to take shortcuts instead of strictly following some more or less well-established rules. There is, however, a desire within the scientific community to ensure high-quality results in general. This provides a solid base for future work, allows for fair evaluations of the work, and helps to ensure that money for science is used in a trustworthy way in order to secure further public support.

One overruling ethical principle, illustrated in figure 8.9, must be stated as a core in the ethos of science: Science should be a systematic attempt to observe the world

Figure 8.9. *Three monkeys* by the Swedish artist Torsten Renqvist (1924–2007), a representation of the East Asian maxim 'See no evil, hear no evil, speak no evil'. As usual, one monkey covers the ears, and one covers the mouth. The third, who traditionally covers the eyes, here cannot refrain from looking. Renqvist, with a strong interest in science, commented: 'He sees, and so he must. He is the one who has bitten of the apple.' Photography: Kristina Backe.

accurately and report its findings honestly. This requirement of truthfulness may seem obvious. Trust in the scientist and the scientific community that the new knowledge will indeed be beneficial for humanity, or at least not be harmful, is certainly widespread. Yet history and contemporary examples demonstrate that striving for truth is not obviously present or even generally accepted in the world. This is partly related to the fact that truthfulness sometimes causes problems for the individual scientist.

Important ethical dilemmas are involved in the selection of science projects and as regards the responsibility for the application of the results. Even if the ambition of the scientists is simply to provide fundamental knowledge, only they may be able to understand the possible consequences of their findings. This issue has, however, been discussed previously [178–180] and will not be treated here.

8.5.2 Ethics of the science process

We shall discuss the ethics of scientific work, noting that many of its conventions and ethical rules aim to promote truthfulness. In addition to honesty and objectivity, care and solidarity relative to colleagues are stressed. Certainly, these virtues are also significant in the society at large, but the demands are much stronger in the scientific community. These ethical requirements are set in order to guarantee the quality of the scientific results in the service of the needs to accumulate and apply knowledge.

A term for the upholding of these virtues is *scientific integrity*[5], which more specifically means avoiding fabrication and falsification of data, bias, plagiarism, and carelessness, all in order to guarantee objectivity, reproducibility and trust in results and reporting.

Here, I shall discuss some aspects of these principles and present associated areas where science plays important roles and where ethical problems arise. A discussion follows on possible actions to be taken by the science community and various authorities to uphold these principles. I shall not discuss ethical problems relating to the social life in research groups and institutions with leadership, power structures, or improper dependences. Although important, these topics are not limited to the scientific work environment.

8.5.3 Forgery

Wikipedia lists a depressingly extensive list of scientific misconduct incidents over the last two decades [181]. The list includes more than 110 entries[6]. Among those are over 70 forgeries, in which data were fabricated or systematically changed. There are papers in which identical sets of data were used to represent alleged outcomes of different and unrelated experiments. In other cases, data from certain experiments were used to represent data from experiments which were never carried out. A

[5] The term was introduced in *Best Practices for Ensuring Scientific Integrity and Preventing Misconduct*, OECD. 2007, https://www.oecd.org/science/inno/40188303.pdf (retrieved May 30, 2021).

[6] Another measure of scientific misconduct gives the data base of retracted papers https://retractionwatch.com/retraction-watch-database-user-guide/, although many papers have been retracted for other reasons. By October 2020 more than 24 000 retracted papers were listed.

relatively common type of forgery has been manipulation of images. These were possible to discern via careful studies by journal editors and referees. The forgeries abound in all fields, from physics and chemistry and biology to social sciences. They are found in different nations and institutions, from leading universities to small, less well-known places. An overrepresentation in medical work, including false statistics and unmotivated lethal experiments on patients, is particularly worrying [182]. Thousands of scientific papers have been retracted as the result of the disclosure of these forgeries.

One may speculate about the reason for these behaviours. Some of the cases seem truly pathological or due to personality disorders of histrionic or narcissistic personalities. Several of them seem to be demonstrations of alleged invincibility ('See what I can do, and nobody can hurt me!') or deliberate self-destruction. However, in studying these cases, another and worrying fact soon becomes clear. The cases are often suspicious in the sense that remarkable and unexpected 'results' are presented. In itself the selection of discovered cases may be heavily biased towards such results. Such cases are prone to be scrutinized, and, if falsifiable, to be disclosed by the community. Cases in which data seem more innocent or expected may have a larger chance of remaining undisclosed. Thus, fraudulent scientists who are anxious to remain undiscovered while generating extensive publication lists should be expected to avoid publishing unexpected results. One may therefore speculate that a consequence of this dishonesty may well be a retarding force on scientific progress.

How common are such less obvious falsifications? According to a metastudy by Daniele Fanelli [183], about 2% of scientists who were asked admitted that they had at least once fabricated or modified the data presented, while about 30% admitted that they had been involved in other questionable research practices. When asked whether the scientists had colleagues who had ever fabricated or modified data, the percentage increased from 2% to 14%. About 70% said that they had colleagues who had showed misconduct in other ways.

8.5.4 Plagiarism

Another type of scientific misbehaviour is plagiarism, which is taking someone else's ideas or work and presenting them as one's own. This was quite common in earlier epochs [184] and may not have hurt the progress of science much. However, the practice of stealth promotes secrecy, which may be harmful in our scientific culture which benefits so much from exchange of ideas and experiences. Today, with the contemporary stress of careers based on extensive publication lists, the temptation to plagiarize may be hard to resist.

Among the examples of plagiarism in the Wikipedia list [209] are a number of stolen publications or sections from work by graduate students or postdoctoral researchers. There are cases of papers to be refereed that were delayed or stolen by unscrupulous researchers, who subsequently published the work as their own, or stolen from other authors who have published in less well-known journals. In some cases, tens of papers were republished and misattributed to one individual. However, such plagiarisms are now easily traced via modern detection software, when the stolen work is available in public databases.

When studying the plagiarism cases more closely, one finds that in several cases, carelessness or a stressing timetable might be reasons. This may occur when reviews are to be produced for conferences or review journals, and excerpts are taken from various sources, including self-plagiarized ones, and in the next stage are 'forgotten' to be properly acknowledged[7]. A possible measure to diminish this problem would be to reduce the number of review papers, for example, replacing them by 'living' reviews, continually updated by experts.

It is noteworthy that a number of leading politicians, including some at the ministerial level, have been caught with plagiarism in their doctoral theses. Even though plagiarism seems to be a fairly common in the political culture, judging from the presence of numerous cases of stolen political speeches, it is astonishing that this culture trumps the more rigorous demands of honesty in the academic enterprise.

More difficult to trace, and presumably more common, is citation plagiarism, in which articles or other work is used with inappropriate citations. Another related form is bibliographic negligence, in which important work, preceding the present work and of great significance for it, was not referred to at all [185].

8.5.5 Reviewing science

The discovery of frauds in published science journals has cast doubts on the peer-review system. Obviously, any expectation that the system is free from fraud is unrealistic even while it provides some control on the quality of journal papers. The steadily increasing number of papers, driven by the demand for extensive publication lists in applications for jobs or resources, is also a threat to the system. There are difficulties in finding suitable referees and for those referees to find time to do a diligent job [186].

Other reviewing tasks, in nomination committees for positions, panels for grant allocation, and other forms of evaluations, also entail ethical dilemmas. A major reason for these problems is again the growing volume of publications, reflecting the growth in the number of applications, in combination with the requirement of repeated controls. Within the new public management (NPM) approach for making public services more 'businesslike', models from the private sector are introduced into the academic world with the aim to make it more efficient [187]. With such a system the number of evaluations may become excessive. This number should be kept at a minimum via longer grant periods, more tenure-track positions, and a robust allocation system of resources to research groups and departments.

8.5.6 Shadow zones: boasting

Although central in the scientific endeavour, truthfulness is not always fully respected in scientific enterprise. There is a clear tendency in applications for jobs

[7] Conversely, reviews are often used to prepare the introductory sections in papers without proper references. Information about the true origin of data or ideas may thus be lost in this process in several steps.

or grants and in other presentations to exaggerate the significance of the results that are obtained. This ‘boasting’ seems to have increased in volume and aggressiveness during the last decades, which may be a consequence of the fierce competition for jobs and money on the research market, now highly affected by the practices of NPM.

In an attempt to explore boasting, expressions of self-overestimation were searched for in several hundred applications for junior staff positions in natural and technical sciences at Uppsala University [188]. Although this study was methodologically problematic, clear differences were found depending on the origin of the applicants and their respective fields. The closer the research area was to industry or commercial applications, such as information technology, biomedicine, and technology, the more frequent were words such as ‘world-leading’ ‘excellent’, and ‘successful’, while such words were sparser in applications for jobs in mathematics, astronomy, physics, and fundamental chemistry. Interesting differences were also found in the degree of boasting between applications from different countries.

In a parallel study of the official web pages of different Swedish universities, very clear differences were found. The more established institutions with higher positions on international ranking lists had a lower degree of boasting, while the new ones, generally dependent on support from local regions and industries, more often presented themselves as ‘excellent’. The technical universities had higher boasting indices than the classical ones with broader programmes. This again points to influences from the commercial sector being stronger when academia is closer to, or more dependent on, that sector.

These studies illustrate how the academic and commercial cultures interact and affect each other [189], including their demands for truthfulness.

Several universities now systematically train young scientists to ‘sell themselves’ on the international labour and grant markets. It is important to study whether the respect for accuracy and truthfulness in scientific judgements is hollowed out by that. One might hope that the next generation, trained in handling the commercial flow in media, will be able to distinguish between the language used in the market versus that used in scientific dialog.

Another type of boasting occurs when science journals overemphasize the significance of results that they present, probably exaggerated for commercial reasons and applauded by authors who seek approval and resources by financing agencies.

8.5.7 Shadow zones: the replication crisis

Reproducibility is a fundamental requirement for scientific work and demands control of experiments and observations and on reporting the methods and results. A paper with the provocative title ‘Why most published research findings are false’ by Ioannides [190] demonstrated the need to have very large samples with controlled bias in statistical studies in order to acquire safe demonstrations of causal relations. Similarly, Ziliak and McCloskey, in a book with another provocative title [191], examined a great number of economics papers and argued that only about one fourth of them showed reproducible results. A few years later, it was demonstrated that papers in social sciences as well as in social psychology, pharmacy, and medicine presented results that could not be reproduced, even by the scientists who had made the original study. This led to the introduction of the catch term 'The replication (or reproducibility) crisis'. A *Nature* poll of 1500 scientists in 2016 indicated that about 70% of them had not succeeded in reproducing results of at least one other study [192] ; indeed, half of them could not even reproduce one of their own reported findings. The results differed between areas; physicists and chemists showed the greatest trust in the published results, while medical and social scientists had less confidence. In this survey, the scientists were also asked about the reasons for the low reproducibility and what could be done to improve it. More than 60% responded that two reasons were particularly important: pressure to publish and selective reporting. Missing checks in the lab and too small sample sizes were also pointed out. When asked about how the reproducibility could be improved, more than 90% suggested 'more robust experiment design', 'better statistics', and 'better mentorship'. The current strong tendency in favour of open data [193] and open-source code [194] may contribute to relieving the replication crisis.

8.5.8 Shadow zones: cherry picking and the sheep–goat effect

One reason for the lack of reproducibility is no doubt more or less conscious cherry picking; that is, we tend to select the data we believe in and disregard the data that seem less probable to us. As much as this may lead to problems with reproducibility, it may also cause too much of it. Thus, the 'sheep effect' may result from cherry picking. As has been pointed out in several critical studies of the measurement of certain important quantities, 'classical values' tend to be replicated in repeated studies with a precision that is higher than realistic error estimates should permit. The background may be a consequence of the complexity of modern laboratory experiments and computer codes. The efforts to debug the equipment and the programs are cumbersome and tend to be pursued until reasonable—expected—results are produced. At that stage, the incentive to continue the debugging is considerably reduced, in particular if time is short, which is often the case. Thus, the results that are presented may have a bias towards the expected values.

However, there may be another factor of significance: the welcoming of somewhat different values, which may then make it easier to publish the result, just because it seems to be more interesting than a simple replication. The study of stellar chemical abundances (a study which needs a number of steps in which judgment plays a role that is hard to automate) contains such examples. Results from different determinations 'jump' between different seemingly converged values as a function of time [195]. I named that that the 'sheep–goat effect' in 2004. A corresponding effect was also traced in molecular genetics research and dubbed the 'Proteus phenomenon' [196].

8.5.9 Shadow zones: authorship

The principles of assigning authorship of papers are much discussed and certainly have ethical aspects. One question concerns the criteria for coauthorship. The International Committee of Medical Journal Editors (ICMJE) recommends authorship to be based on the four criteria [197]:

'(1) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; (2) Drafting the work or revising it critically for important intellectual content; (3) Final approval of the version to be published; (4) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. … In addition, authors should have confidence in the integrity of the contributions of their coauthors.' These rules seem to be frequently disrespected by medical faculties in Sweden [198].

Often, the contributions are not significant in all these respects but may be specific in just one or two of them. In many cases, the contribution may be limited to some important idea, may be limited to some aspects such as the construction of equipment or computer programs used, or may already have been presented in previous papers. In other cases, the main contribution by a given author may be the writing of applications to secure sufficient funding for the research. Which of these different contributions is required, and how significant should they be, in order to earn a coauthorship?

Comparative studies, such as [199], show that in this respect, the culture in different fields, journals, institutions, even research groups at the same department may be quite different in spite of many local attempts to establish common practices. In some institutions a rather rigorous principle is established, restricting the authorship to those individuals who have taken part in the project from the beginning, have written parts of the final report, and are able to present and defend the project fully at an international symposium without drawing back from certain questions with the excuse 'I did not do that part'. In other places, there may be the habit of including anyone who is a member of a research team even if they contributed nothing to the paper in question.

Individuals who are included in the author list of an article without having contributed substantially are generally called 'honorary authors' or 'guest authors'. There may also be important contributors who are not included in the list, known as 'ghost authors'. In an extensive survey [200], the prevalence of honorary and ghost authorship in high-impact biomedical journal papers was found to be typically 20% for both categories.

The ICMJE rules admit another category, contributors, for individuals who have made important contributions to the paper but who did not meet all of the stated criteria. It seems that this option, with specification of what each contributor has done, would be worth adopting in wider circles. This would make it clear which individuals are most responsible for the paper as a whole, while giving proper credit to those who have contributed important parts but should not be held responsible for the paper in total.

Another issue for which the cultures are very different is the order of authors. As long as these conventions are understood and agreed on within the research group and its peers, the ethical problems are limited, although it may be important both for evaluators and users of the science presented to know who is most responsible for the work.

However, considerable ethical issues may lurk in these lists of names. 'Guest writers' appear in many lists. Typically, they are individuals with well-known names who are listed in order to give credibility and status to the science that is presented, as payment for various types of support, in exchange for positions in author lists of the guest's own projects, as 'consolation authors' whose own project did not go very well and so more papers were needed for the PhD thesis, or as 'decoys' which are there as encouragements to recruit young scientists to the group. Such bad manners may not mar the publications as such, but they certainly disturb the career and reward system which today is so dependent on publication statistics. In the worst case, this practice may lead to a culture wherein which scientific results and papers are produced for which nobody takes full responsibility.

One should realise that authorship of science papers may be bought for some tens of thousands of dollars without the purchaser having contributed any research at all [201]. This shows how publication of science papers is becoming another market.

8.5.10 Popular science and teaching the public

The monkey on the right in figure 8.9 is supposed to see *and* report what it sees and not only to the other monkeys on the bench but also to the beholders, to the public. For publicly financed science the obligation to communicate the ideas, results, and prospects of the research activity to the public should be obvious, at least in democratic states. An ethical problem, however, is how this is done.

All science communication, not least popularization, requires simplification. To simplify in a truthful way is an art in itself. If it is done with the aim of bringing forward a particular point, that bias must be balanced by presentation of other reasonable views, in particular if the speaker or writer, as is often the case, is trying to make a particular point or advocates a personal view. The requirement of a balanced presentation is at least as strong as what one should demand from any scientific paper. In the popularization case we cannot expect the recipients of the message to see the proper counterarguments and form their own balanced view. The contrast between our habit in science to require peer reviews of our manuscripts and project proposals while presenting our science subjectively to the public is striking.

In recent decades there has been a clear tendency among universities and other stakeholders of research to professionalize public communication by hiring public relation professionals with the ambition to give a rather glorious picture of science in general and their institution in particular. The need to attract more attention, funding, and students may be understandable, but it is unfortunate if one tries to attract these by selling the activity through exaggerated arguments. In the long run, public respect for science in general and the institution in particular may be eroded.

Figure 8.10. In a 1999 article in *National Geographic* this fossil was claimed to be a 'missing link' between terrestrial dinosaurs and birds. It was later shown to be a composite of fossils from several different species [202]. The forged 'Archaeoraptor liaoningensis' specimen is on display at the Paleozoological Museum of China. Photo: Jonathan Chen.

In popular presentations such as books, TV programmes, or exhibitions (as in figure 8.10), one rather often finds anecdotes or curios that are false but remain unchallenged for decades or even centuries. If you ask the authors about this, you may get the answer that 'that story is too good not to be told'. The balance between the desire to entertain and the need to inform correctly must not be lost. The nobility mark of science, the strong ambition to be truthful, should be dominating and visible in all our activities.

One very important aspect of teaching science to the public is to try to counteract superstition in an era of systematically spread misinformation ('fake news'), sometimes presented in a misleading scientific disguise, and as something that 'research has proven' without any sources given. It is nontrivial to foster balanced critical attitudes without eroding trust in science and truth as such. It is an obligation of scientists to contribute to this teaching in collaboration with schoolteachers and journalists, avoiding elitist attitudes as far as possible.

8.5.11 Science advice

The role of a science advisor to decision makers, whether in the public sector or industry, is delicate. Truth should always be presented as objectively as possible. A central question remains: Should the scientific advice be limited to presenting the factual circumstances while refraining from further value-based conclusions on what actions should be taken? After all, the scientist does not work from the direct mandate of the public and is not accountable to voters, unlike the politician in democratic states. This is an argument for the scientist to avoid being involved in the decision making. However, one may also argue, following Douglas [200], that scientists, being more knowledgeable in certain situations, are best equipped to foresee the moral and political implications. They should, if they meet ignorance or misunderstanding among politicians, consider giving concrete political advice.

An example was presented by the HBO TV series *Chernobyl*. Here, the physicist Legasov, beginning to suggest an evacuation of the nearby populations to minimize the radiation damage (which the politicians underestimated or did not understand), is told that his advice should be limited to 'answer direct questions about the function of the reactor …, nothing else'[8].

The balance between loyalties to the decision makers and to the scientific community is another difficult balance for the advisor. My advice from personal experience in this respect would be that support from experienced mentors is vital.

8.5.12 Attempts to strengthen integrity and ethical awareness in science

A most obvious consequence of the forgery of scientific data and of other dishonest presentations of science, including plagiarism, is that the most qualified scientists may be hindered from getting positions or grants due to competition from less honest colleagues. A number of universities and funding agencies have introduced measures to reduce this risk. One of these, which is not very common, is to improve the reviewing process by giving more time and resources to experts involved in the evaluation and demanding more details from the applicants. For university research, much evaluation is basically in the hands of the science journals but could be complemented by a local review process at the universities, although this brings some risk of inappropriate censoring. Another measure is to install severe sanctions against cheaters, such as stopping funding of their projects, firing them from their positions or membership of committees or learned societies, retracting their papers from journals, or, if laws apply, bringing them to court. Such measures have been taken in a number of cases. It is, however, not clear that this has contributed very efficiently to the solution of the problem in view of its magnitude and its partly hidden character, as discussed earlier in this chapter.

Another countermeasure against forgery of scientific results and other bad practices is to promote the awareness within the scientific community of the need for scientific integrity. During the last decades a great number of initiatives have been taken in this direction, by international organizations, national authorities and universities. The US Office of Research Integrity and the European Science Foundation established a World Conference on Research Integrity with a first meeting in Lisbon in 2007 followed by one in Singapore in 2010, which produced a 'Statement on Research Integrity' [203], and a sequence of additional meetings about every second year, with hundreds of participants in each from the scientific community and administrative bodies, including some top officials. The themes discussed at these meetings have gradually widened, including self-regulation measures with peer reviews, replication and retraction, proper teaching of younger scientists, and systemic problems in research that undermine integrity and possibly generate misbehaviour. These problems were coupled to research funding structures

[8] For an interesting discussion, see Silk M S W 2019 The ethics of scientific advice: lessons from 'Chenobyl'. *The Prindle Post*, Ethics in the News from the Prindle Institute, July 26, 2019, https://www.prindlepost.org/2019/07/the-ethics-of-scientific-advice-lessons-from-chernobyl/ (May 2, 2021).

and processes, competition among researchers and institutions, and career systems. Further aspects discussed were the replication crisis, the role of media and outreach, quality control in laboratory contexts, and industrial research [204].

A number of different international organisations have set up research ethics committees that at times work on integrity issues and give relevant recommendations concerning those. The International Science Council, with a broad coverage of disciplines and countries, is advised by its Committee for the Freedom and Responsibility in Science to promote the freedom for scientists to pursue knowledge and interact but also to take responsibility to maintain high science ethical standards. Several organisations with universities as members, such as the European University Association, which has more than 800 universities as members, are important as platforms and bases for establishing ethically acceptable practices in research.

Several codes of conduct have been established through such organisations. For instance, the European federation of Academies, Allea, has established a European Code of Conduct [205], which is recognized by the EC as a reference document.

On the national level, a large number of initiatives have been taken by research agencies and universities, establishing ethical committees and procedures with the aim of preventing misconduct among their grant holders or employees. As bases for the work of the committees, rules of conduct have been produced[9]. Initially, the committees were in most cases organised as part of the respective agency or university. This is still so in many cases, for instance, for the proactive bioethic committees that have to approve research projects that involve animals or humans before grants can be allocated to them. For the reactive committees that handle reports on suspected misconduct by individuals, several countries have appointed committees that are independent from universities in order to reduce tendencies to suppress locally embarrassing cases, or even misuse the local committee to legitimate nonethical actions[10].

Another reason for appointing national committees is to ensure consistent nationwide criteria and sanctions. Formally, these committees should not be regarded as courts. Their task is to give recommendations to funding agencies and employers, which have the mandate to take action if the misconduct is not forbidden by law. If it is, the case may proceed to a regular court. However, it is not obvious what the adequate consequences should be. All sorts of reactions by the agency or employer occur, from friendly notices to firing. In practice, a committee decision that a certain behaviour is judged to be reprehensible may have a very severe impact on the future working conditions and career of the individual scientist and his or her research group: it may eventually lead to a professional ban. In view of these serious consequences, even in cases in which the sanctions are limited, the needs for possibilities and procedures for appeal have been stressed. Likewise, methods and

[9] One example is *Good Research Practice*, Swedish Research Council (2017), https://www.vr.se/english/analysis/reports/our-reports/2017–08–31-good-research-practice.html

[10] For examples of misusing the local ethics review committees for reputation management, see [192].

routines for rehabilitation of scientists who have been found guilty of misconduct are called for[11].

In spite of the arrangements mentioned previously, it is unclear whether scientific misconduct will be reduced. The possibilities for reporting suspected misconduct may keep the numbers of obvious fraud and plagiarism cases low, but it is uncertain whether less obvious, more cunningly constructed forgeries and citation plagiarism, 'bibliographic negligence', or authorship trading is affected at all. Courses and conferences on research ethics raise awareness in the scientific community, and exposure of misconduct offers interesting insights into human psychology, but it is uncertain whether these will really decrease the misconduct, any more than courses in criminology can be expected to reduce the crime rate. Such initiatives serve not only to make scientists aware of the integrity problems, but at least as much to make decision makers and funding agencies aware of the ambitions in the scientific community to come to terms with these problems.

8.5.13 Strengthening ethical behaviour by relaxing competition

If one aims at reducing the misdemeanours of scientists, one could try to harness one of its probable causes: the increased competition for positions and resources. For a discussion of this, see the review by Fang and Casadevall [207]. Classically, competition was regarded as beneficial to the scientific endeavour, stimulating scientists to work hard and publish swiftly [208]. This view is still common, not least among funding agencies. In recent decades, several groups have expressed their findings (or fears) that the strengthened competition, or 'hypercompetition', generates bad practices [209, 210], such as preventing others from using the methods developed, interfering with peer-review processes, poor publication habits, carelessness, and partial and unfair evaluations of the work of competitors. Fears have also been expressed that the competition scares young scientists, maybe in particular females, away from scientific careers [211].

Fang and Casadevall [207] argue that competition is not essential for good science. On the basis of neuropsychological and experimental psychology results, they suggest that in fact competition may have detrimental effects on creativity, citing the psychologist Theresa Amabile, who argues, on the basis of experimental studies of children, scientists, and technicians, that interest, enjoyment, satisfaction, and challenges in the work itself, not external motivators or pressures, are main factors in creativity. She describes a work environment that relies on external financial rewards, creates relentless deadlines, and subjects any proposals to 'time-consuming layers of evaluation, … and excruciating critiques' as counteracting creativity [212] and concludes that 'job security appears to be extremely important in fostering creativity' [213].

In an attempt to determine whether the conclusions of Fang and Casadevall are valid in a contemporary North European context, I prepared a small exploratory study with a questionnaire among staff and graduate students at physics and

[11] For rehabilitation of wrongdoers, see [206].

astronomy departments in the Stockholm–Uppsala region. In this I asked questions as to whether the effects of competition were mainly positive or negative in terms of quality of science, well-being of scientists, and whether competition attracted scientists and students to research or pushed them away from it. The vast majority of the respondents argued that the competition for jobs and resources was mostly negative for the well-being and recruitment of scientists, and most respondents also argued that negative effects dominated for science as such. Most positive answers came from well-established and well-supported senior professors. Noteworthy, however, was that the negative views of competition which were so dominant among the younger scientists also prevailed among the emeritus professors.

Fang and Casadevall claim, on the basis of studies of the origins of innovations in science and technology, that competition, if it prevents cooperation, is counterproductive.

From this discussion it seems natural to tentatively conclude that relaxing the competitive staging of the research career and financing systems would lower the degree of unethical practices in contemporary science. The effects of such reforms could also lead to more creative science and more collaboration within and between different research areas. Also, the recruitment of very talented but less competition-oriented young scientists would be beneficial. It thus seems possible that science at large would gain from such a relaxation. Further studies of the effects of competition may be warranted. However, there could be challenges for funding agencies where authority and power are partly based on the competition system itself.

Reforms to relax competition and enhance collaboration and creativity may include the science culture, career systems, and distribution of resources. For instance, concepts such as science as a Darwinian struggle in which only winners survive, the main focus is on priority in discoveries and innovation, and only principal investigators are celebrated may be toned down. A better balance between workforce and resources, sealing 'leaky pipelines' in the career flow, and long-term commitments for funding agencies, with grants given more to able groups and individuals than to short-term projects, could be considered [214]. An interesting question is whether the scientific community could abstain from the stimuli of fierce competition and instead embrace the joy of collaboration and discovery of our remarkable world.

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8.6 The limits of science

8.6.1 Technical, fundamental, and epistemological limits of science

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In recent decades, a gap between two kinds of physical reasoning has opened up. Applied physics and phenomenological physics show all the basic characteristics of canonical 20th century science. But fundamental physics, represented by high-energy physics model building, quantum gravity, and cosmology, faces substantially new challenges that influence the nature of the scientific process. Those shifts can be expected to become even more conspicuous in the period up to 2050. Exploring their full scope will arguably be an important task for fundamental physics in upcoming decades.

The 20th century was a hugely successful period in fundamental physics. Developments from the advent of relativistic physics and quantum mechanics to advanced theories in particle physics played out based on the general expectation that physicists would find theories that could account for the collected empirical evidence in a satisfactory way and could (with some exceptions) be empirically tested within a reasonable time frame. In stark contrast to the 18th and 19th centuries' absolute trust in Newtonian mechanics, however, 20th century physicists assumed that none of the theories they were developing would be the last word on the general subject they addressed. Theories that were successful at the time would eventually be superseded by more fundamental ones. Physicists thus were highly optimistic about their future achievements but avoided declarations of finality with regard to any theory at hand.

Early 21st century physics finds itself in a very different place. This section will focus on three aspects of the new situation: the long periods of time in which influential theories remain without empirical testing, the long periods of time in which theories remain conceptually incomplete, and the issue of finality in contemporary physics.

8.6.1.1 Limits to empirical access

In high-energy physics, the last theory that has found empirical confirmation is the standard model, which was developed in the late 1960s and early 1970s. The empirical confirmation of the standard model's many predictions was completed in 2012 with the discovery of the Higgs particle[12]. Theory building from the mid-1970s onwards has advanced far beyond the standard model, however. New theories were motivated in various ways. Some characteristics of the data, though not contradicting the standard model, found no satisfactory explanation on its basis. More

[12] The only data-driven adaptation of the standard model happened in the late 1990s when the massiveness of neutrinos was empirically established. That feature could be accounted for within the standard model framework in an entirely coherent way, however.

substantially, quantum field theory, which provided the conceptual foundation for the standard model, was inconsistent with general relativity, the theory that described gravity. General characteristics of gravity imply that the strength of the gravitational interaction becomes comparable to the strength of nuclear interactions at a high energy scale (called the Planck scale). To describe physical processes at that scale, a new theory is needed that describes gravity and nuclear interactions in a consistent way.

During the last 50 years, the described lines of reasoning in conjunction with others have led to the development of influential theories beyond the standard model. Grand unified theories, supersymmetry, and supergravity introduced larger symmetries within the context of gauge field theory. String theory aims at full unification of all fundamental interactions by reaching beyond the confines of conventional gauge theories. Various conceptual approaches aim at the quantization of gravity from a general relativistic starting point. In cosmology, the theory of inflation provides an entirely new view of the very early phase of the universe.

Up to this point, none of the mentioned theories has achieved empirical confirmation of its core predictions. Nevertheless, some theories have been quite strongly endorsed by its exponents. The most striking example is string theory [215], which was presented in 1974 as a fundamental theory of all interactions based on replacing the point-like elementary particles of quantum field theory by extended one-dimensional objects, the superstrings. From the late 1980s onwards, string theory has assumed the status of a conceptual basis and anchoring place for much of fundamental physics. Exponents of string theory think that they have very strong arguments for the theory's viability even in the absence of empirical confirmation[13]. Critics of string theory, on the other hand, deny any epistemic justification for an endorsement of the theory in the absence of empirical confirmation [216].

A slightly different case is cosmic inflation [218]. The theory of cosmic inflation lies at the core of large parts of contemporary cosmological reasoning. It aims to explain some very general features of the niverse that would seem *a priori* inexplicable within the context of general relativity, and to account for characteristics of cosmological precision data. To that end, it posits an early phase of extremely fast (exponential) expansion of the universe. In contrast to string theory, quantitative implications of models of cosmic inflation can be confronted with empirical precision data. The theory is widely taken to be in very good agreement with available cosmological data. Many of the theory's exponents have a high degree of trust in the hypothesis of inflation on that basis. Critics of inflation take that trust to be unjustified, however. They emphasize the theory's lack of conceptual specificity, and they doubt the confirmatory value of seemingly supporting empirical evidence [219].

[13] Contact between string theory and characteristics of our world that does not reach the level of significant confirmation has been made in the research field of string phenomenology [217].

Maybe the most fundamental problem for conclusive empirical confirmation arises with respect to the multiverse hypothesis [220] [14]. Based on conceptual considerations in inflationary cosmology, the multiverse hypothesis posits that vast numbers of universes are generated in an exponentially expanding background space. We live in one of those many universes and, according to the present understanding, cannot possibly make any observations beyond the limits of our own niverse. The existence of the other universes therefore may be inferred based on theoretical considerations but can never be empirically confirmed. Exponents of the multiverse point out that there can be empirical confirmation of the multiverse theory based on the theory's predictions regarding our own universe. Critics of the multiverse argue that the in-principle lack of empirical access to core objects posited by the multiverse hypothesis nevertheless infringes on the principle of testability of scientific theories [221].

In all three described contexts, physics faces the problem how to deal with the absence of, or complications regarding, the empirical testing of fundamental physical theories. These problems can be expected to continue in upcoming decades and raise the general question as to what counts as a viable epistemic basis for seriously endorsing a scientific theory. Obviously, the scientific process will sustain its efforts to develop effective strategies for empirical testing wherever possible. Empirical confirmation will remain the ultimate and most trustworthy basis for endorsing a theory. A question that will become increasingly important, however, is how to assess the status of well-established theories in the absence of sufficient empirical confirmation. A research process where scientists often spend their entire career working on a theory without seeing that theory conclusively empirically tested raises this question with urgency. Characteristics of fundamental physics today may indeed offer a basis for epistemic commitment that reaches beyond the canonical confines of empirical confirmation. A philosophical suggestion to that end has been presented under the name nonempirical (or more specifically metaempirical) confirmation [222].

As was described previously, scientific praxis in recent decades has led many theoretical physicists towards having substantial trust in empirically unconfirmed or inconclusively tested theories, while other physicists have strongly criticized that process. The developments in physics in the upcoming decades will move this issue forward, one way or another. If further developments vindicate trust in theories such as string theory or cosmic inflation based on empirical confirmation, nonempirical arguments, or both, this will increase the willingness of theoretical physicists to strongly endorse theories even in the absence of strong or any empirical confirmation. In that case, physical reasoning in 2050 will be based on a significantly extended concept of theory confirmation. If trust in the above theories erodes for whatever reason, the focus will move back towards a more traditional understanding of theory assessment.

8.6.1.2 The chronic incompleteness of fundamental theory building

The second problem faced by fundamental physics may be even more significant from a conceptual point of view: fundamental theories in physics become

[14] The multiverse plays a pivotal role in the influential and much debated anthropic explanation of the fine-tuned cosmological constant.

increasingly difficult to spell out in a complete form. In some cases, such as the case of cosmic inflation, this problem is directly linked to the theory's limited empirical accessibility, which stands in the way of specifying the conceptual details of the theory in question. But in other cases, such as string theory, the core of the problem seems distinct from issues of empirical access.

String theory has been conceptually analyzed since the late 1960s and was proposed as a theory of all fundamental interactions in 1974. Fifty-five years of work on string theory, including four decades when a substantial part of the theoretical physics community has contributed to developing the theory, have not brought string theory anywhere close to completion. The theory today amounts to an enormously complex system of conjectures, elements of formal analysis, and calculations achieved based on simplifications or approximations. In conjunction, these strands of analysis provide a considerable degree of understanding of the coherence and cogency of the overall approach and the ways in which many of its aspects are intricately related to each other. Still, the theory's core remains elusive.

As described earlier, the development of the conceptual understanding of string theory has not found guidance in empirical data. Such data, if available, would obviously be very helpful for further conceptual work on the theory. However, the data would not in themselves provide the basis for solving the conceptual core problem: how to pin down the full formal structure of string theory.

The difficulties in developing a full-fledged string theory have their roots in quantum field theory, which was developed to describe interactions between highly energetic (that is very fast-moving) elementary particles starting in the 1930s. Calculations of specific quantitative empirical implications of quantum field theories can be extracted only on the basis of perturbation theory, which is a method of approximation. Perturbation theory provides highly accurate and reliable quantitative predictions of specific particle interaction processes if the interactions involved are weak (in a well-defined sense). For strong interactions, the method breaks down. String theory was initially developed as a perturbative theory along the conceptual lines of perturbative quantum field theory. Two aspects of string theory render the use of perturbative methods more problematic than in the case of quantum field theory, however. First the full theory to which perturbative string theory is an approximation is still unknown. Therefore, perturbative string theory serves not merely as an approximation scheme but also as an essential indicator of the character of the unknown theory to which it is supposed to be an approximation. Second, string theory has no (dimensionless) free parameters. Therefore, interaction strength, like all other parameters of low-energy physics, must emerge from the full dynamics of the theory. Thus, the reliability of the perturbative method cannot be a universal feature of string theory. At best, it could be extracted for a given regime from a nonperturbative analysis of the fundamental theory. Compared to conventional quantum field theory, the understanding of string theory thus is overly dependent on a perturbative perspective, and there is an urgent need to reach beyond it.

Recent decades have led to a deeper understanding of string theory that reaches beyond the perturbative perspective. A crucial role in these developments has been played by duality relations that establish weak and strong coupling regimes of seemingly entirely different types of string theory (and beyond) to be empirically equivalent [223]. No breakthrough towards a full understanding of the mechanisms that guide nonperturbative string theory has been achieved, however. The elusiveness of a full formulation of string theory at its core in this light is a conceptual problem rather than a problem of empirical access.

The problem is not confined to string theory. All approaches to quantum gravity that choose different starting points than string theory, such as loop quantum gravity or spin foam, have encountered similar problems. After decades of work on those approaches, they have not led to a complete theory. It is not even clear whether a coherent theory of gravitation in four extended spacetime dimensions can be formulated on the basis of those approaches.

The problem thus seems to arise once theory building aims at the level of universality needed to join the principles of quantum physics necessary for understanding microphysical phenomena with the principles that govern gravity. While 20th century physics has achieved a satisfactory understanding of those two realms of fundamental physics in separation, the 21st century may be expected to be devoted to bringing them into a coherent overall conceptual framework. It is exactly this context where the substantial roadblocks described above arise.

It will be the main task of fundamental physics in the upcoming decades to further attack those difficulties. But the substantial shift in the time scales for completing theories of fundamental physics may lead fundamental physics towards reevaluating its understanding of scientific progress altogether. Since the 19th century, this understanding has been based on the principle of theory succession: Theories are being developed within a reasonable time frame, to be empirically tested soon thereafter. Empirical tests could lead either to the theory's rejection or to its confirmation as a viable description of nature within a given empirical regime. Further tests would then test the theory's predictions with increasing accuracy until a disagreement between data and the theory's predictions was found. Such empirical anomalies could then lead to the development of a new theory that replaced the old one as the viable fundamental theory.

The timelines for empirical testing have been stretched to an extent that renders the canonical view of the scientific process insufficient. In this section we point out that the canonical view is drawn into question at a conceptual level as well. Scientific progress in 21st century fundamental physics may not amount to formulating complete scientific theories.

Today, this shift of perspective is merely a possibility. It may still happen that, by the year 2050, revolutionary changes in physics will have turned a full theory of quantum gravity into an imminent prospect or even into reality. If so, the current suspicion of a long-term change of theory dynamics would have turned out to be a transient impression provoked by a particularly difficult phase of theorizing.

If, however, the period up to 2050 prolonged the current step by step conceptual progress towards a better understanding of an elusive theory of quantum gravity, this would strengthen the case for acknowledging a lasting and substantial shift in the scientific dynamics of fundamental physics. The process of theory succession that characterized 19th and 20th century physics would seem to have been replaced by a different mode of the scientific process that is represented by continuous work on and an improving understanding of one theory or theoretical framework without prospects of formulating a complete theory in the foreseeable future. The completion of that theory would appear to be a remote endpoint of the process of physical conceptualization rather than an imminent goal for the individual scientists. To what extent that new dynamics amounted to a manifestation of fundamental limits to science and to what extent it should rather be viewed in terms of an altered concept of scientific progress would then emerge as a core question for the status of physics in the 21st century.

8.6.1.3 Signs of finality

A third important shift that has occurred in fundamental physics in recent decades is directly related to the issue of acknowledging a new phase of the scientific progress: Fundamental physics today is more conspicuously associated with issues of finality of theory building [224] than 20th century physics.

Throughout much of the 20th century, physics shunned any suggestion of finality in physical theory building for two reasons. First, the revolutions of special and general relativity and quantum mechanics served as omnipresent reminders that even with regard to a theory that was as dominant, successful, and long-living as Newtonian mechanics, claims of finality had been misplaced. Second, it became increasingly clear that the incoherence between the principles of quantum mechanics and general relativity would require at least one more fundamental conceptual step before arriving at a fully consistent overall understanding of theoretical physics. All empirically successful theories in 20th century physics were therefore understood to be viable at most up to those energy scales where predictions had to account for gravity and nuclear interactions at the same time.

When attempts to develop a theory of quantum gravity took center stage in fundamental physics in the last quarter of the 20th century, this situation changed. The second reason for not considering issues of finality ceased to apply, since quantum gravity amounted to the projected conceptual step that had prevented finality claims regarding previous theories. Moreover, the appeal of the first reason was considerably weakened as well. Quantum gravity provided new reasons for taking finality claims seriously that went beyond anything that could have been said in support of the finality of Newtonian mechanics in the 19th century. The 19th century finality claims regarding Newtonian mechanics were based simply on the enormous and longstanding success of the theory in multiple contexts and the lack of evidence that suggested that it needed to be superseded. The empirical testing of processes where very high velocities, very small objects, or very high gravitational forced were involved did eventually reveal empirical inconsistencies with Newtonian mechanics that led to the revolutionary new theories that superseded it. Nothing in Newtonian physics apart from a crude meta-inductive assumption that a theory that has worked in so many contexts should work everywhere would have, in advance, spoken against the possibility of such an outcome.

General considerations on the nature of quantum gravity provide a stronger basis for a final theory claim. To understand the basic idea, one needs to remember once again how physics has changed in the 20th century. From a 19th century perspective, velocities, distances, and mass values were independent parameters. Special relativity then established that an object's mass was a form of energy (just like its kinetic energy), and quantum mechanics made it possible to view distance scales in terms of inverse energy scales. The move towards higher energy and respectively smaller distance scales thus became the one central guideline for finding new phenomena in fundamental physics. Quantum gravity now suggests that the notion of distance scales smaller than the scale where gravity becomes roughly as strong as nuclear interactions (the so-called Planck scale) may not make sense, due to a fundamental limit to information density. String theory, viewed by the majority of physicists to be the most promising approach of quantum gravity, offers a deeper understanding of this limit (in terms of a specific feature called T-duality) [225]. These arguments do not conclusively establish finality because their soundness relies on the truth of the theory or conceptual framework on whose basis they are developed. Nevertheless, they turn questions of finality into genuinely physical questions.

The issue of finality stands in a complex relation to the issue of chronic incompleteness addressed in the previous section. On the one hand, chronic incompleteness makes it more complicated to understand what could even be meant by a final theory claim. How is it possible to assert the finality of a theory whose full formulation is not in sight? At a different level, however, the final theory claims raised in quantum gravity seem in tune with the phenomenon of chronic incompleteness. Like chronic incompleteness, final theory claims may be taken to suggest that the paradigm of scientific progress that was prevalent throughout the 20th century is inadequate for characterizing the scientific process in 21st century fundamental physics. Based on the canonical paradigm of scientific progress, a final theory claim regarding a universal theory such as string theory would imply the completion of fundamental physics within the foreseeable future. Once one replaces that canonical paradigm by a principle of chronical incompleteness, however, nothing of this kind follows. In that view, the projected point in time when fundamental physics will have been completed has not come closer. What has changed is the nature of the scientific process that leads towards that point. Rather than a sequence of superseding complete theories, it would be step-by-step progress towards an improved understanding of the one universal and final theory physicists are working on already but whose completion is not in sight.

If the upcoming decades of physical research strengthen the tendencies described in this text, fundamental physics in 2050 will be a very different enterprise than fundamental physics half a century ago. Its new character will arguably change the human understanding of the nature of scientific reasoning. The three described developments are distinct but carry a coherent overall message. As long as physics deals with limited sets of phenomena, it is the physicist's task to identify those phenomena that allow for the development and empirical testing of appropriate theories within a reasonable time frame. Once physics approaches a fully universal fundamental theory, however, leaving out what seems too difficult to include stops being an option. Physics thus faces a situation where problems too difficult to solve and phenomena too remote to be empirically tested at the given point all live within the scope of the universal theory that is being developed. Achievable research goals in this new environment shift from the complete formulation and conclusive testing of the theory towards the more modest goals of solving specific problems within the overall theory, confronting the theory with empirical data to the extent possible, and assessing the theory's status based on all information available. Within this new framework, just as before, physics will pursue its old but still distant ultimate goal: to find a full and consistent description of the physical world we live in.

8.6.2 The future of humankind and behaviour

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8.6.2.1 Fascinating physics

Discovering and visualizing gravitation waves accompanying the collision of two black holes have been a megaevent for astrophysics and for theoretical physicists remembering Albert Einstein's theory of general relativity, which predicted the existence of such waves [226].

A technological mega-adventure is it to copy on the Earth the energy production in the Sun's plasma by letting billions of deuterium and tritium atoms fuse into helium and a neutron. In Cadarache, 50 kilometres north of Marseille, the International Thermonuclear Experimental Reactor is under construction [227].

Understanding the solid-state and fluid-state physics of the vitreous body of the human eye is essential for ophthalmologists confronted with a patient's mechanical indentation stemming from a car accident [228].

These are three examples out of hundreds of fascinating (and often useful) discoveries or textbook results of modern physics. In some cases, such as in the physics of the eye, the usefulness is evident. In others, such as in the Tokamak fusion reactor, the usefulness for providing huge amounts of energy is still a guess. In some fields of physics, such as black holes and gravitation waves, humanity may never find practical advantages but will appreciate the scientific excellence. Moreover, the experimental setup leading to the visualization of those mysterious waves is likely to produce useful byproducts.

8.6.2.2 Known and unknown dangers

In 1938, Otto Hahn and Fritz Strassmann found the chemical element barium after shelling neutrons on uranium and were highly suprised. Lise Meitner, Hahn's earlier colleague, emigrated to the US, immediately explained that the uranium atoms must have been split. So far, it was just fascinating pure physics and chemistry. Otto Hahn rightly won the Nobel Prize (in chemistry) for it. But instantaneously, physicists around the world became aware of a huge potential of a new method of producing useful energy. Simultaneously, they also became aware of immense dangers resulting from atomic explosions using the uranium splitting.

This is perhaps the best-known example in history of the findings of physics leading to a nightmare. Atomic weapons soon became an immensely important factor for the politics of power.

Physics, chemistry, and, since the discovery of genetic engineering, biology have become ingredients of science fiction novels with a tendency to emphasize the dangers and rather underestimate the enormous benefits emerging from the natural sciences.

As we look towards the Horizon of 2050, it will be wise to further develop human understanding of the dangers and of methods of analysing and controlling them. We will need a political consensus that innovations in the sciences should be accompanied by technology assessments addressing potential dangers of criminal abuse or technological failures.

8.6.2.3 The limits to growth

Of course, dangers are not always caused by technological or scientific discoveries. Rather more often, dangers can arise from conventional developments. Wars, pandemics, famine, and crimes have caused disasters throughout human history. In some rare cases, disasters are looming just from the continuation of benign and highly popular activities.

Over the millennia, humans have always tried to create good lives for themselves, notably by overcoming hunger or famine and healing curable conditions and diseases. Nobody would have blamed such efforts as the causes of dangers or disasters. Creating economic growth has been the desire and plan of politicians around the world. But then, in 1972, a shocking book was published that expressed the unthinkable, namely, that continued growth might eventually lead to very unpleasant collapse events for the simple reason that the size of planet Earth was limited and was therefore in straightforward conflict with unlimited economic growth. The book was called *The Limits to Growth* [229]. It resulted from research initiated by the Club of Rome, which was founded in 1968.

What was and what is that mysterious Club of Rome? Its founders were Aurelio Peccei, an unusually gifted and successful Italian business man (Fiat, Olivetti) with a strong focus on world justice, and Alexander King, head of the OECD's science department. In 1968, they brought together some 20 like-minded people in Rome to discuss 'the predicament of mankind'. One systems scientist of the group was Professor Jay Forrester of the Massachusetts Institute of Technology, who had developed a smart computer programme, called Dynamo, allowing the estimation of future developments of several factors mutually influencing each other. Forrester offered to bring a team together for using Dynamo for tentatively deciphering the predicament of mankind.

The team, under the leadership of Dennis and Donella Meadows, did an impressive job calculating or rather estimating the predicament for food, mineral resources, industrial output, population, and pollution. Dynamo allowed the production of impressive visuals. The standard run of the programme ended up producing the graph shown in figure 8.11.

The book became an unprecedented world bestseller. It was translated into all major languages and sold more than 30 million copies. For the broad public, it was a shock. Growth, after all, was the symbol of a better life, more freedom, more mobility, and the end of hunger.

The assumed exhaustion of natural resources was the biggest shock. How could humanity survive if natural gas and oil or copper and iron would no longer be available? One group of countries, the Organization of Oil Exporting Countries (OPEC) was also shocked, but some in OPEC soon conjectured that oil scarcity also meant that oil countries held a very powerful weapon in their hands. Oil, after all, was one of the most demanded natural resources. In attempting revenge for the Yom Kippur War of October 1973, Arab oil-exporting countries pushed the price per

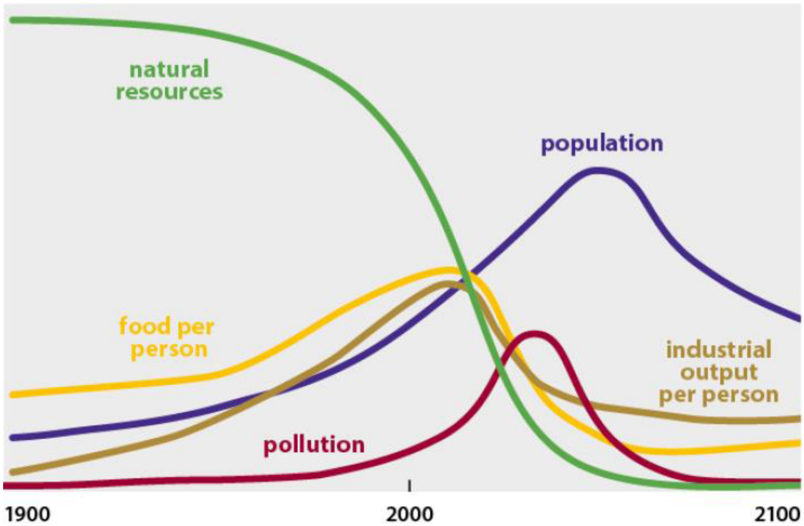

Figure 8.11. The world model brought five parameters together, mutually influencing each other. The influencing factors were empirically established from the first 70 years of the 20th century. One conspicuous prediction was the exhaustion within 100 years of natural resources (green curve). In consequence, food and industrial output per person and the human population were also sharply reduced.)Source: Meadows *et al*, p 124 [229] CC BY 4.0. The picture is styled for easy reading.)

barrel of oil from the low level of US$3 up to US$12 with the intention of punishing the countries which had supported Israel. Indeed, the price shock led to an oil crisis that caused an awful stagnation in the industrialized world.

However, one of the predictable consequences of oil scarcity and elevated oil prices was a strongly intensified worldwide oil exploration and exploitation. This turned out remarkably successfully, leading to an oil glut. The glut defeated many of the assumptions of *Limits to Growth.* Systems theory, by that time, was mature enough to realize that computer programmes must include the possibility of major changes in initial assumptions.

Nevertheless, some commentators still attempted to justify the logic of *Limits to Growth* because the basic message was so plausible. One such attempt came from Graham Turner [230], who 'updated' the *Limits to Growth* model, essentially by replacing oil scarcity with the need to reduce CO_2 emissions. It is surely correct that 40 years after the oil crisis the major concern is no longer the absence of cheap oil but global warming, caused by too much burning of fossil fuels. But in terms of the geological and mathematical correctness of the *Limits to Growth* assumptions, this is pure nonsense.

8.6.2.4 The real scare is planetary boundaries

Nevertheless, Graham Turner and other authors are right that the basic message of *Limits to Growth* has remained valid since the publication of the famous book. On the other hand, Johan Rockström and others managed to shift the discussion away from the simplistic Dynamo models towards more realistic concerns over specific scarcities. The first major publication of Rockström's team was published in 2009 under the title *Planetary boundaries: exploring the safe operating space for humanity* [231, 232]. The concept indicates, based on scientific research, that since the Industrial Revolution, human activity has gradually become the main driver of global environmental change. Once human activity passes certain thresholds or tipping points (defined as 'planetary boundaries'), there is a risk of 'irreversible and abrupt environmental change'. Rockström *et al* identified nine 'planetary life support systems'that are essential for human survival and attempted to quantify how far they have been pushed already.

The nine planetary boundaries are as follows:

- Stratospheric ozone depletion
- Loss of biodiversity and extinctions
- Chemical pollution and the release of novel entities
- Climate change
- Ocean acidification
- Land system change
- Freshwater consumption and the global hydrological cycle
- Nitrogen and phosphorus flows into the biosphere and oceans
- Atmospheric aerosol loading.

Surprisingly, the authors identify only two boundaries that are already in a state of high risk: genetic diversity (as part of the loss of biodiversity and extinctions) and nitrogen and phosphorous flows into the biosphere and oceans. Climate change and land system change are still located in the domain of increasing risk. This early assessment is surely up for debate. In our day and time, we would be more concerned with global warming, including its effect on weather escapades and the rise of the sea level.

8.6.2.5 The anthropocene

Closely related to the planetary boundaries and the safe operating space is the more descriptive definition of the 'Anthropocene'. The same Will Steffen and coauthors Paul Crutzen (Nobel Prize of Chemistry 1995) and John McNeill, coined the term [233]. They show that after the seven epochs of the Cenozoic geologic era (since some 66 million years ago), we humans have begun to massively interfere with the geological status of the planet. This gigantic human intrusion into the robust geologic and atmospheric conditions of the Earth has brought the last 'natural' epoch, the Holocene, to an end. Now, we humans are creating and dominating a new epoch. That new epoch hence should be named after its major driving force, which is humankind. In the ancient Greek language, humans are called *anthropoi*. That is the origin of the new name, Anthropocene.

Figure 8.12 shows several empirical trends of human origin (in red), and the resulting trends of physics and chemistry of the planet's condition (in green). Each of the 24 small pictures contains a thin vertical line, which marks the year 1950. It is

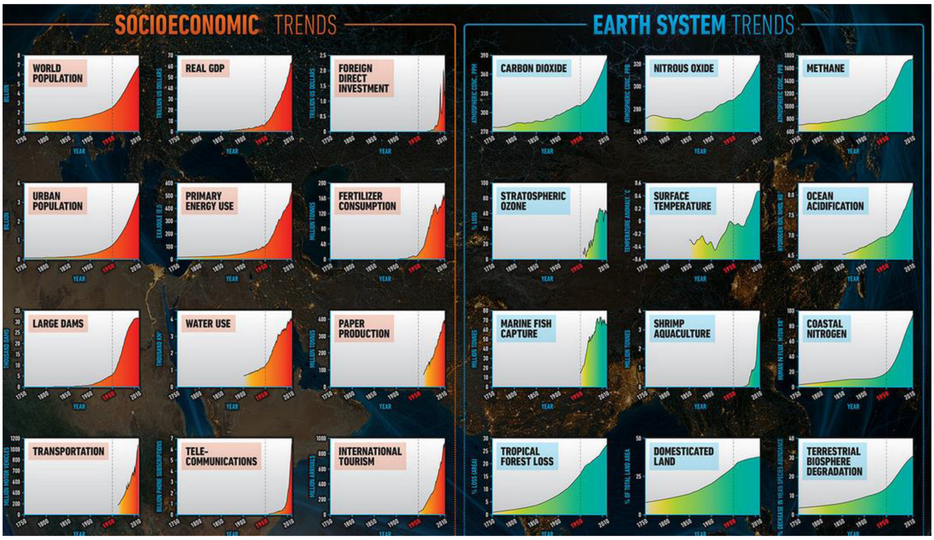

Figure 8.12. The Great acceleration of the Anthropocene. Twenty-four curves showing the dramatic changes of human population and other socioeconomic patterns (red) and Earth system changes (green). The dramatic changes occurred after 1950. (Source: Steffen *et al*, 2015 [234] with permission from Sage.)

quite surprising that thousands of years of human presence on the planet did not significantly alter the physics and chemistry of the planet, but the past 70 years have caused a biogeochemical revolution.

What is the message in all this? It says that humanity has quite recently entered a completely new historical period, in which our responsibility has begun to include the need for extremely cautious attitudes towards our planet.

It is no exaggeration to say that the fate of human society at the Horizon of 2050 will depend on the development of exactly such cautious attitudes.

8.6.2.6 A new enlightenment?

European civilizations emerged from the 'dark' Middle Ages with an enormous amount of fresh thinking in terms of logic, precise observation, and the establishment of 'natural laws' of astronomy, physics and chemistry. Also, rational and legal rules were established for the functioning of statehood and society. Moreover, European explorers and armies began to 'conquer' the rest of the planet, using technological and military advances based on scientific findings. The period in Europe from the 16th to the 18th centuries is often called the Enlightenment period. To be sure, continents outside Europe suffered considerably from the mostly arrogant and brutal European intruders. But nobody would deny that scientific understanding and philosophical clarity greatly benefited from exactly this Enlightenment.

On the other hand, the troublesome developments of the limits to growth, the population explosion, and the Anthropocene were consequences of that same Enlightenment. When we as humanity are forced to analyse and overcome our self-inflicted troubles, we can better also consider some philosophical shortcomings of the old European Enlightenment.

The new strategic Report to the Club of Rome, published in 2018 for the fiftieth anniversary of the Club, puts this consideration at its centre. The Report is called *Come On!* [235], and it contains three chapters with two different meanings of *Come On!*

1. C'mon! Don't Tell Me the Current Trends Are Sustainable!
2. C'mon! Don't Stick to Outdated Philosophies!
3. Come On! Join Us on an Exciting Journey Towards a Sustainable World.

'Don't stick to outdated philosophies' means to go beyond the anthropocentric, utilitarian, analytical, reductionist philosophy that was characteristic of the Enlightenment. We as authors discovered that some of the philosophers of the Enlightenment, including Adam Smith, are systematically misinterpreted in modern economics. At the time of Adam Smith, the geographical reach of the law and the geographical reach of the market (the 'invisible hand', according to Smith) were identical. This made for a benign balance between the market and the law. But today, markets are chiefly global, and the law remains chiefly national, if not provincial. Global financial markets, on their permanent search for maximised returns on investment, are free to identify places with the weakest laws. They actually blackmail national lawmakers to weaken laws, reducing social security costs, as a condition for the investors to invest there. Downward spirals of legal and fiscal conditions can be observed [236]. That benefits the rich and further impoverishes the poor.

We also looked at David Ricardo's description of the relative comparative advantages of different countries leading to international trade optimising cost–benefit ratios. But Ricardo at his time assumed that capital remained immobile. Under today's condition of extremely high capital mobility, we see that absolute comparative advantages determine the location of production. This gives capital markets extremely strong powers over the real economies, leading to unruly fluctuations and big losses on the part of many countries.

The neoliberal economic philosophy after massive deregulations, chiefly after the year 1990, essentially benefits the owners and speculative traders of capital and tends to create billions of losers. Also, the natural environment tends to be losing because of the enormous acceleration of all processes shown on the left side of figure 8.12.

8.6.2.7 Balance instead of dogmatism

Considering the unintended disadvantages of economic (and religious) dogmatism, we as authors felt that it was time to resurrect the philosophies of balance. We know that Asian cultures have a long tradition of balance. Mark Cartwright [237] offers a simplified definition of what is also an essential part of Confucian cosmology: 'The principle of Yin and Yang is a fundamental concept in Chinese philosophy and culture. … This principle is that all things exist as inseparable and contradictory opposites, for example female-male, dark-light, and old-young. The two opposites attract and complement each other and, as their symbol illustrates, each side has at its core an element of the other. … Neither pole is superior to the other and, as an increase in one brings a corresponding decrease in the other, a correct balance between the two poles must be reached in order to achieve harmony.'

Somewhat related philosophies exist in the West, such as G W F Hegel's dialectic philosophy and Ken Wilber's *A Brief History of Everything.* Also Niels Bohr's complementarity has been seen by Frithjof Capra [238] as a 'door-opener' to perceiving parallels between modern physics and Eastern wisdom and religions.

We cannot here go into the fairly complicated parallels between physics and (Eastern) philosophy. Instead, I am listing examples of balances which make a lot of sense in understanding the practical usefulness of the balance concept.

We propose to seek a balance between the following:

- Humans and nature: Using remaining natural landscapes, water bodies, and minerals chiefly as resources for an ever-growing human population and the fulfilment of ever-growing consumption is not balance but destruction.
- Short term and long term: Humans appreciate quick gratification such as something to drink when thirsty. But there is a need for a counterbalance to ensure long-term, action such as policies to restabilize the Earth's climate.
- Speed and stability: Technological and cultural progress benefits from competition for temporal priority. Disruptive innovations can bring tremendous benefits. But speed by itself can be a horror for slow creatures, for most elderly humans, for babies, and for communities. The current civilizational addiction to speed is destructive to structures, habits, and cultures that have emerged under the sustainability criterion. Sustainability, after all, includes stability.
- Private and public: The discovery of the human values of individualism, private property, and protection against state intrusion has been among the most valuable achievements of the European Enlightenment. But in our times, public goods are much more endangered than private goods. The state (public) should set the rules for the market (private), not the other way round.
- Women and men: Many early cultures developed through wars during which women were chiefly entrusted with caring for the family and men for defence (or aggression). This model is outdated. Riane Eisler [239] has offered archaeological insights into cultures that thrived under partnership models and has also shown that the conventional, male-dominated 'wealth of nations' is almost a caricature of real well-being [240].
- Equity and awards for achievements: Without awards for achievement, societies can get sleepy and lose out in the competition with other societies. But there must be a publicly guaranteed system of justice and equity. Inequity, according to Wilkinson and Pickett [241], tends to be correlated with very undesirable social parameters, such as high criminality, poor education, and high rates of infant mortality.
- State and religion: It was a great achievement by the European Enlightenment to separate public from religious leadership, fully respecting religious values and communities. Religions dominating the public sector are

in high danger of destroying human rights and an independent legal system with independent high courts. On the other hand, states that are intolerant of religious communities tend to lose touch with ethical (and long-term) needs.

Many more pairs can be formulated showing that balance is essential for a high and sustainable level of culture. Exact physics does not contradict this insight. Dogmatism is always allowed in checking the validity of scientific methods, mathematical calculations, and technological applications. But arrogance of science against nonquantitative insights and goal seeking is usually counterproductive.

8.6.2.8 Conclusion

Society at the Horizon of 2050 will predictably be massively concerned with geophysical phenomena related to global warming and with biological tragedies of accelerated extinction of species. Good science will be much in demand for maintaining, enhancing, and applying measures to stop destruction and to regenerate healthy conditions for the stability of our planet. But historians will emphasize that humanity has, by a simplistic and materialistic 'pursuit of happiness', destroyed much of the earlier richness of nature.

First-class physics will maintain its high appreciation by the public under the condition of conversely appreciating the strong desire of society for long-term strategies of sustainable development and for modesty of consumption.

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