

Physics education for 21st century graduates

Diane J Grayson

University of the Witwatersrand, Private Bag 3, WITS 2050, South Africa
Diane.grayson@wits.ac.za

Abstract. The 21st century world in which today's students are growing up is different in a number of important ways from last century. It is characterised by ubiquitous and increasingly sophisticated technology, accelerating climate change, globalisation, and the concentration of the bulk of the world's wealth in the hands of an ever-decreasing percentage of its population. There was also the great recession of 2008. Taken together, these things are impacting on students' thinking patterns, behaviours, expectations, constraints and opportunities. Broad global developments, such as the fourth industrial revolution, the United Nations Sustainable Development Goals, as well as the recent rise of so-called fake news and popular rejection of evidence-based thinking, frame the context for what we can and must do in educating our students. What are the implications for physics and physics teaching? Physicists have always maintained that learning physics develops ways of thinking and solving problems that have broad applicability. While that may be true, no human endeavour can ever be divorced from context. How is the teaching of physics being affected by the global context, and how can physics teaching contribute to addressing global challenges? In this paper, I present key characteristics of who we are teaching, and make suggestions, in broad terms, about what and how we should teach in order to equip our students to be successful 21st graduates. That involves being able to navigate the complexities and uncertainties of a turbulent world, today and tomorrow, and, hopefully, contribute to making it a better place for all of its inhabitants.

1. Introduction

The 21st century world is different from previous centuries in a number of ways, which has important implications for those involved in education. The rapid growth and effects of the human population on the earth are significantly, and almost certainly irreversibly, changing the planet and the future of its inhabitants, both human and non-human. Scientists have established that human activity, particularly the release of large amounts of carbon dioxide and methane into the atmosphere, is fuelling a rise in the average temperature on earth [1], which is affecting climate globally, and with it, food security and the fitness of different regions for human habitation. Partly as a result of human population growth and global warming and partly through other unsustainable, and, in some cases, unethical or illegal, practices, biodiversity is decreasing at an alarming rate [2]. According to the 2018 Living Planet Index, wildlife populations have decreased by 60% between 1970 and 2014 [3]. Plastic production is escalating – 44% of all plastic has been manufactured since 2000 – and an estimated 18 billion pounds of plastic waste is entering the world's oceans every year [4], where an increasing number of marine animals get entrapped by it or ingest it, either in macroscopic or microscopic form. Recent scientific evidence shows that microplastics are entering the human food chain and emerging in human waste, with unknown consequences for human health, especially if the particles are small enough to enter the bloodstream [5].

The global distribution of wealth is becoming increasingly skewed. Unlike 50 years ago, today the bulk of the wealth is in the hands of a tiny proportion of the population, while the proportion of middle income earners is shrinking and of those living in poverty is increasing. Figure 1 shows global wealth distribution in 2017.

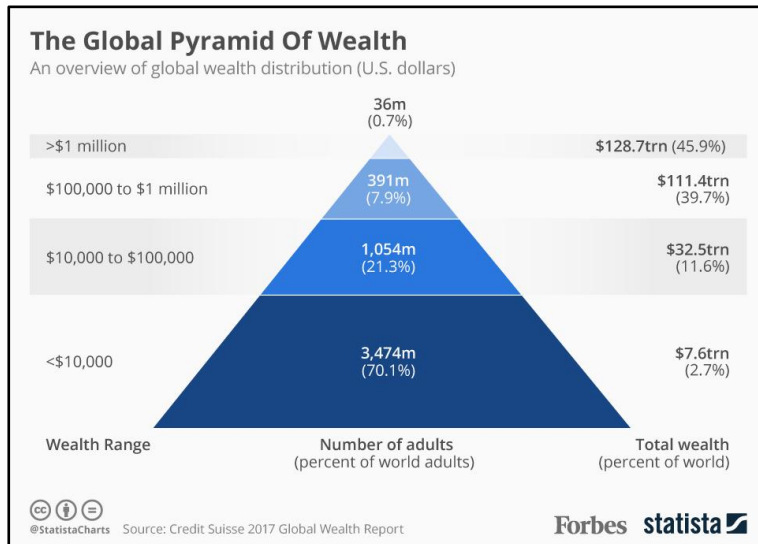


Figure 1. The distribution of global wealth in 2017.

Another feature of the 21st century is the rapid rise in the speed and availability, and decrease in price of, information and communication technology, as well as the astronomical increase in data produced. It is estimated that 2.5 quintillion bytes of data are created daily, and over half of the searches of the internet are conducted on a mobile phone [6]. The sheer volume of data and ease with which it can be created, accessed and distributed mean that digital channels of communication are open to abuse. In the last two or three years attention has been drawn to a rise in “fake news”, which is being spread rapidly and extensively on social media and the internet in order to untruthfully promote the interests of a particular person or group. In an interim report to the UK House of Commons, several categories of “false information” that are typically associated with the term “fake news” are identified, namely, content that is fabricated, manipulated, imposter, misleading or associated with false contextual information [7].

While greater electronic connectedness, particularly through social media, can be beneficial to establishing and maintaining relationships and sharing information, it can also hinder meaningful communication. In a prescient piece written more than two decades ago, physicist David Bohm said [8]:

“In spite of this worldwide system of linkages, there is, at this very moment, a general feeling that communication is breaking down everywhere, on an unparalleled scale... What appears [in the media] is generally at best a collection of trivial and almost unrelated fragments, while at worst, it can often be a really harmful source of confusion and misinformation.”

A very recent feature of the global context is the identification of what is being termed the “Fourth Industrial Revolution”, flagged in 2016 by the founder of the World Economic Forum [9]:

“We stand on the brink of a technological revolution that will fundamentally alter the way we live, work, and relate to one another. In its scale, scope, and complexity, the transformation will be unlike anything humankind has experienced before. We do not yet know just how it will unfold, but one thing is clear: the response to it must be integrated and comprehensive, involving all stakeholders of the global polity, from the public and private sectors to academia and civil society.”

The contextual features of the 21st century raised above have implications for physics teaching now and in the future. In this paper I will consider some of the implications for who we teach, what we teach and how we (should) teach.

2. Who we teach

At present the bulk of our students are “millennials”, people born between 1980 and 2000. Many articles have been written about how millennials differ from previous generations. In 2013 *Time* magazine published a special issue on millennials [10]. Some of the features common to many millennials, at least in developed countries, are that they:

- Are individualistic, narcissistic, seek recognition and approval and are easily discouraged;
- Want “me” time, flexible work schedules, experiences above things;
- Do not bow to authority, tend to be very confident and optimistic;
- Have a short attention span, are hooked on social media but are not necessarily computer or digitally literate¹;
- Enjoy networking and collaboration, but mostly with peers (not adults) and not so much face to face as digitally;
- Have little experience with “tinkering”;
- Are likely to be less affluent than their parents, more likely to live with parents than with a spouse.

Millennials have grown up with social media. They are the most photographed generation ever, often by themselves. Photos taken by oneself – “selfies” – are now an everyday phenomenon in popular culture and there are companies that produce “selfie sticks” that can be attached to a cellphone so that photos of oneself can be taken from further away and thus avert the distortion that comes with close up photos or the need to communicate with someone else (as in the old-fashioned way of asking a passer-by, “please would you take a picture for me”). The frequent posting of selfies on social media has given rise to an increase in narcissistic behaviour and other psychiatric disorders [11]. There are also concerns that when adolescents expose themselves so readily and so frequently to public (or nearly public, when they have large social networks) view at a time when they are establishing their identity, it may interfere with the development of healthy self-esteem and acceptance of their own physical appearance [12].

It is interesting to note that while millennials are often called “digital natives” because they grew up with the internet, they are not necessarily computer literate. For many millennials, their interaction with ICT is confined largely to the use of social media and the internet, and often on mobile devices rather than on computers. As a result, they do not necessarily know how to use word processing software or spreadsheets, tools that educators from the previous generation take for granted, let alone identify when a cable is loose or write a simple computer program. In addition, while they might be able to “surf the web”, they may well not be able to locate or identify evidence-based information from trustworthy sources.

Another difference between millennials and previous generations is that they are less likely to “tinker” with physical objects using what older people consider “everyday” tools – screwdrivers, wrenches, hammers and pliers. This trend has led the iconic Swedish company, Ikea, pioneer in the production of furniture kits that are assembled at home, to buy a company that assembles furniture for its customers [13]. Some people argue that the increased time that millennials spend in the digital world

¹ Computer literacy refers to being able to carry out simple tasks on a computer, such as sending emails, saving files in different formats, or browsing the internet, and to use basic application software, such as word-processors and spreadsheets. Digital literacy is regarded as a form of media literacy. It involves being able to work in meaningful ways with content that is available digitally, such as on websites and social media.

as opposed to the “real” world is affecting their ability to carry out “everyday” life tasks, such as cooking or basic home repair, and perhaps even how their brains are being wired as a result of less manipulation of physical objects [14].

In addition, the global economic recession in 2008 had a serious impact on millennials, many of whom, as a result, have struggled to find good jobs and are still living with their parents when they are in their 20s and even 30s, rather than striking out on their own or starting their own families. This trend, combined with an increased proportion of social interactions taking place electronically, is altering how millennials relate to other people. This last point is even more salient for the generation coming up behind the millennials, Generation Z.

Members of Generation Z were born after 2000, and are about to enter colleges and universities. A survey conducted in the USA of over 1000 13-17 year-olds in 2012 and again in 2018 [15] showed that the proportion of teenagers whose preferred mode of communication with their friends is face-to-face dropped from 49% to 32%, as shown in Figure 2.

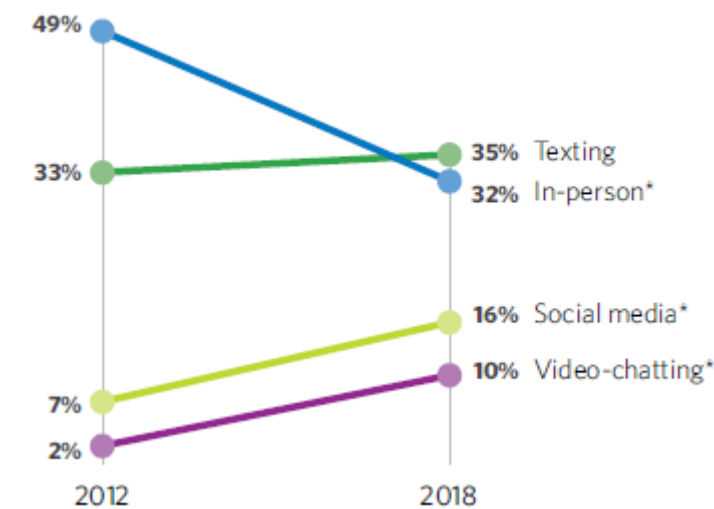


Figure 2. Preferred mode of communication with friends for 13-17 year olds in 2012 and 2018.

* Differences over time are statistically significant at $p < .05$.

Other common features of Generation Z members are that:

- Many are affected by anxiety and depression;
- They tend not to be too good at teamwork;
- They are anti-branding and advertising but like “cool stuff”;
- They go to YouTube to learn anything, including how to solve homework problems (!)
- They prefer Snapchat (which deletes posts) to Facebook;
- They are entrepreneurial.

Research suggests that depression among teenagers, the leading edge of Generation Z, is increasing [16]. In a 2018 report from the USA, the incidence of depression diagnosed among 12-17 year-olds has risen 63% since 2013 [17]. Some psychologists suggest that the increased use of social media, with the attendant risks of cyber-bullying and unrealistic comparisons with others who may present more favourable images, at the expense of face-to-face interactions may be a contributing factor [18].

3. What we should teach

What are the implications of the global context and the changing profile of our students for what we should teach? Some aspects of what we should teach have been important for decades and remain important today. The core elements of physics are concepts, principles, models and theories. These powerful building blocks enable physicists to describe, explain and predict physical phenomena, from the realm of the smallest elementary particles to the outer reaches of the universe. It is important that we identify for students key concepts and principles that are universal, such as conservation of energy, while making clear what the limits of applicability are of particular theories, such as Newtonian, quantum or relativistic mechanics.

In addition to identifying important elements of physics content to teach, we should also be teaching a number of cognitive skills that are both needed to understand and apply physics concepts and that can be developed through studying and doing physics. Examples of such skills are hypothetico-deductive reasoning, causal reasoning, logical reasoning and translation among different forms of representation (such as diagrams, graphs, equations and words), as well as the set of skills needed to solve problems. Mathematical and computational tools needed for doing physics either need to be developed in physics courses or in other prerequisite or corequisite courses.

Another important component of physics courses, one that is not always explicitly included, is ethics. Students need to understand ethical behaviour, such as avoiding plagiarism and not falsifying experimental results, as well as understanding that ethics plays a role in deciding how physics knowledge might be applied, such as in the development of nuclear weapons. Students should know that there are scientific organisations that take a stand on ethical issues, such as the Union of Concerned Scientists, co-founded in 1969 by physicist and Nobel laureate, Henry Kendall, and the International Union of Pure and Applied Physics, which is committed to the free movement and association of scientists in the world and speaks out against discrimination.

In 2004 the International Conference on Physics Education provided an opportunity to look afresh at what elements should be considered in designing physics curricula. The topic was “What Physics Should We Teach?” [19]. Presentations and discussions were organised into seven strands:

1. Overcoming fragmentation in physics (integrating physics topics)
2. Blurring the boundaries of physics (relationship between physics and other disciplines)
3. Different strokes for different folks (which groups of students need what kind of physics)
4. Origins and ways of knowing (History and philosophy of physics, epistemology)
5. Skills (skills needed for and developed by physics, e.g. cognitive, mathematical, experimental, entrepreneurial)
6. Conceptual organization (selection, sequencing and development of concepts to increase learning)
7. Physics for today (incorporating recent physics developments, technological application)

These seven strands are just as relevant today as they were in 2004. A paper [20] that synthesises and summarises the main issues arising from the conference concludes with a section, Towards a 21st Century Curriculum, which states:

“To this day, physics curricula typically consist of topics whose selection and ordering are guided more by habit or tradition than by cognitive research or sound pedagogy. Fundamental principles and the hierarchical nature of physics knowledge are often not highlighted, with the result that students perceive physics as an impossibly large body of facts and equations to be memorized.

People no longer need to be repositories of large stores of information; that function is better performed by technology. What matters now is how well citizens can access information and what

they do with it. In particular, people need to make judgments about the reliability of information and when and how to use it. Physics courses that are aimed at the acquisition and routine application of selected information will be largely irrelevant to the needs and interests of 21st-century students.

Physicists have generally maintained that the power of physics lies not in a body of knowledge, useful as that may be, but rather in a way of thinking. Now more than ever, that way of thinking should be the focus of physics courses, even if the detailed course content and emphasis are still a matter of debate. The beauty and power of thinking like a physicist involve identifying which of a small set of fundamental principles and key concepts can be used to describe and predict a broad range of physical phenomena.

Physics also provides a rich context within which to teach a wide variety of skills. In addition to the more obvious cognitive and experimental skills, physics courses could help students develop skills that they will need to function effectively in the modern world. The best way for students to acquire skills is to learn them in a specific context and then transfer them to other contexts. This means that teachers of different physics courses must coordinate their offerings and communicate with each other.

A physics curriculum for the 21st century should include the human dimensions of what is a very human activity, the generation of knowledge about the physical world. That knowledge generation does not take place in a vacuum; it is always embedded in a time and place, influenced by history and culture, passion and prejudice. Students should come away from their physics courses with an increased sense of wonder and excitement at the marvels of the physical world and the ingenious ways in which human beings have tried and continue to try to understand them.”

In addition to the skills that have traditionally been considered part of a physics curriculum, albeit tacitly in many cases, there are new skills and ways of thinking that are essential for graduates to be able to thrive in the turbulent 21st century. Four of these, sometimes called the four Cs of 21st century skills, are:

- Collaborative skills
- Communication skills
- Creativity
- Critical thinking

Gone are the days when scientists have the time or money to tinker quietly in their own laboratories. In addition, there is so much information in today’s world, and instrumentation is so expensive, that working with other people on all but the smallest projects is essential. Increasingly, much research work is done in large teams, sometimes extremely large, as is the case in many of the experiments done at CERN. Being able to work effectively and harmoniously as part of a team, and at a later career stage, lead a team, is essential in the modern world. Being able to communicate using a variety of modes and media – speaking, writing, with visual representations and electronic tools and platforms – is also essential. Creativity is needed to address the very complex, “wicked” problems of this age with limited resources and in limited time. Creativity is also a distinguishing feature of what is innately human and what can be done by machines as we advance in this fourth industrial revolution. Critical thinking is essential for distinguishing fact from fiction, particularly with fake news spreading like wildfire, as mentioned earlier.

Other important skills and attributes needed by 21st century students are:

- Life-long learning skills

- Understanding of history and philosophy of ideas
- Global consciousness
- Entrepreneurship
- Interdisciplinarity

Today's graduates are likely to have several distinct careers as a result of rapid changes in the ways in which, and how quickly, information is produced and new technologies developed, and of the nature of work itself. Many jobs that graduates will hold in coming decades do not yet exist, and, indeed, fewer people are likely to hold "jobs" as we know them – being employed by a company or organisation for a fixed salary, working at fixed times, in a highly controlled environment. The ability to continue to learn over a lifetime and to be entrepreneurial are vital for survival in this new world. As the Executive Chairman of the World Economic Forum states [21],

“Catalysing positive outcomes and a future of good work for all will require bold leadership and an entrepreneurial spirit from businesses and governments, as well as an agile mindset of lifelong learning from employees.”

An understanding of the history and philosophy of ideas, while desirable in the past, is essential for the future. With so many potential sources of information, each purporting to espouse the truth, graduates need to understand different ways in which knowledge is created, how it changes over time and how models are formed and elaborated into theories or discarded and supplanted by new ones. We need to teach our students to distinguish between assertions made by those with vested interests, or based on illogical inferences from limited or invalid data, and facts verified by rigorously conducted experiments, careful observations, triangulated qualitative data or derived from a logical chain of reasoning premised on a defensible postulate.

The acceleration of globalisation – the interdependence of people, cultures, economies and goods from all regions and nations of the earth, facilitated by ever-expanding channels of communication – means that students need to understand how to live and work in an interconnected world. Though some may try, it is no longer possible to live in one small corner of the planet cocooned from the influences and effects of others in other places. This is most alarmingly evident in the climate change crisis we are currently facing, as indicated in the introduction. It is essential for our graduates to have a global consciousness, an awareness of how what they do will affect others on the planet and the planet itself.

Another feature of the 21st century is that the boundaries between disciplines as they were defined last century are blurring. There are a myriad of cross-, trans- and interdisciplinary fields that have emerged and continue to emerge. Graduates in the 21st century need to be able to think, study and work across traditional discipline boundaries and with people who come from different disciplinary homes. Engineers now need to learn about community development and environmental sustainability. Artists are working with computer scientists to produce stunning animated movies. For example, an interesting and unusual collaboration between artists, programmers and scientists led to new scientific insights in the making of the film “Interstellar” in 2014. Astrophysicist and Nobel Laureate Kip Thorne was the scientific adviser, and computer programmers and artists used his equations to create visual images (requiring over 800 TB of data), which, in turn, resulted in new scientific knowledge.

Lastly, although there is a corpus of fundamental concepts and laws that physics students need to understand, there is no need to limit what we teach, especially at introductory level, to content that is 50, 100 or 200 years old. There are new and exciting developments in physics all the time, such as the experimental detection of the Higgs boson in 2012 and of gravitational waves in 2015, which, while complicated to explain in detail, can at least be discussed qualitatively. Examples such as these also help

students see that the journey of scientific discovery is long, windy, often unexpected and populated by many people from different places and periods in history.

4. How should we teach?

Before discussing how we should teach, let us first look at what are commonly known as “traditional” ways of teaching. During much of the 20th century most education systems were designed along the lines of a factory model – students typically sat in rows and listened to information presented to them by a teacher in the front of the room. As the number of students at universities grew, this model was taken to an extreme, with hundreds of students seated in a room in front of a single professor who delivered a lecture while the students, in theory at least, sat quietly and “learned”. This arrangement was supposed to be an efficient means of “delivering” education to large numbers of students. However, research has shown that this approach to teaching typically results in very little meaningful, lasting learning. In the words of Arnold Arons [22],

“...much as we dislike the implications, research is showing that didactic exposition of abstract ideas and lines of reasoning (however engaging we might try to make them) to passive listeners yields pathetically thin results in learning and understanding – except in the very small percentage of students who are specially gifted in the field.”

An added challenge to the effectiveness of large lectures in the digital era is that many students are inclined to spend part or all of the lecture time on their electronic devices, engaged in activities unrelated to their studies, such as using social media. In addition, much of the information that might be presented in a lecture is available online, so many students see no need to attend lectures at all.

The other traditional components of physics teaching, assigning homework problems and having students do laboratory work, also present challenges. If the homework problems are standard, end of the chapter problems then students can easily look up the solutions on the internet, or watch them being solved, with explanations, on YouTube. If the problems are more complex or original, the challenge is to get millennials (or Generation Z) students to focus and be prepared to struggle with a problem for more than a few minutes without giving up. Having students work together can help – more about that later. In terms of laboratory work, it is logistically difficult to accommodate large numbers of students in the laboratory. In addition, it is not unusual to find outdated equipment in university laboratories because of financial constraints.

So what can we do? For a start, we can reduce the amount of content we try to “cover”. For several decades, physics education researchers have advocating restricting the number of topics – under the mantra “less is more” – in order to allow students to engage with concepts in greater depth and focus more on developing useful, transferrable cognitive skills. Developing transferrable cognitive skills – ways of thinking and reasoning that can be applied in multiple contexts – is essential for graduates to be life-long learners. The study of physics both requires and facilitates the development of numerous cognitive skills, such as translation among different representations, logical reasoning, causal reasoning and extreme case reasoning. It can also help students develop critical thinking, which is, as mentioned earlier, regarded as one of the essential skills for 21st century graduates. We should, however, be clear about what we mean by “critical thinking”, as it can mean different things to different people. Arons [22] identifies a number of underlying reasoning processes, which may be synthesised to exercise “critical thought”, among which are the following:

- “Consciously raising the question, ‘What do we know...? How do we know...? Why do we accept or believe...? What is the evidence for...?’ When studying some body of material or approaching a problem.

- Being clearly and explicitly aware of gaps in information...Recognizing when one is taking something on faith without having examined the ‘How do we know...? Why do we believe...?’ questions.
- Discriminating between observations and inference, between established facts and subsequent conjecture.
- Probing for assumptions (particularly the implicit, unarticulated assumptions) behind a line of reasoning.
- Drawing inferences from data, observations, or other evidence and recognizing when inferences cannot be drawn.
- Testing one’s own line of reasoning and conclusions for internal consistency and thus developing intellectual self-reliance.”

Although we expect students to develop such skills during their study of physics, we do not necessarily include the teaching of such skills explicitly in physics curricula. Content and skills should be inter-twined in curriculum design like the strands of a DNA molecule. As we teach, we should be explicit about when we are utilising a particular cognitive skill. When we use the skill again in the context of a different topic we should be explicit about that too, highlighting for students how a particular way of thinking or reasoning can be applied in different contexts. And when we assess our students’ learning, in addition to assessing their conceptual understanding, we should also assess their ability to use specific cognitive skills within carefully selected contexts.

Earlier I mentioned that physics can seem to students like an impossibly large body of knowledge to be learnt. One way to overcome this perception is to explicitly show students how physics concepts, principles and laws can be arranged hierarchically. An example is shown in Figure 3 for mechanics.

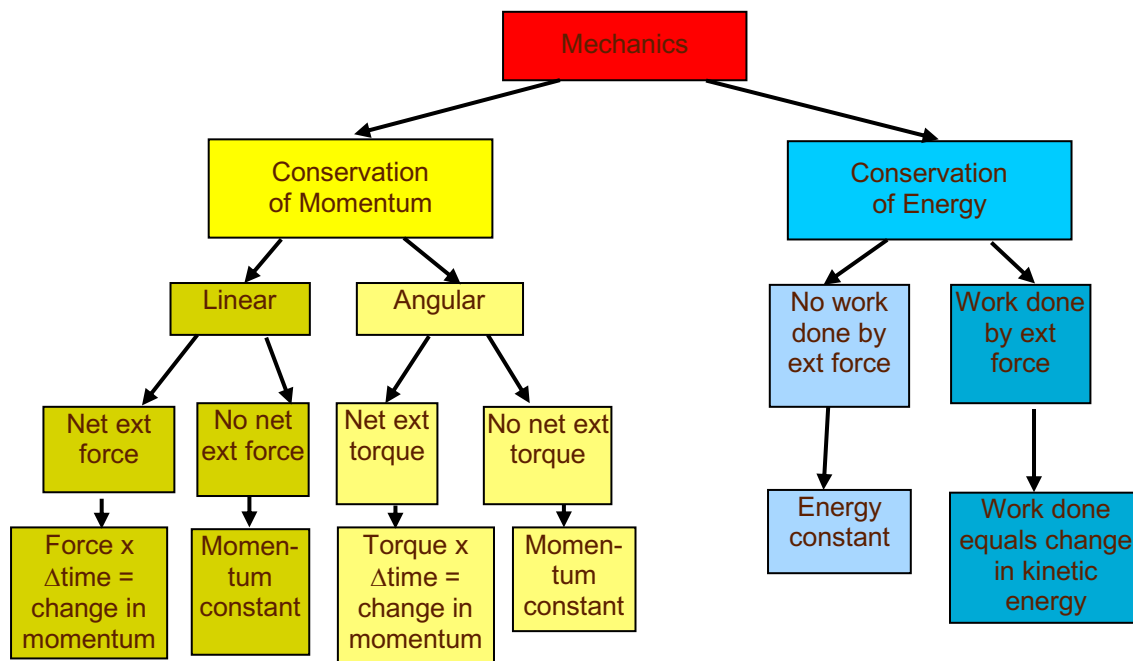


Figure 3. Hierarchical arrangement of laws and concepts in classical mechanics.

The two “big ideas” in mechanics are conservation of energy and conservation of momentum. Momentum is only conserved if no net external force acts on a system; if a net external force does act on a system momentum is not conserved. The change in momentum is equal to the product of the net external force and the time for which it acts, which is the original formulation of Newton’s Second Law

(and more generally applicable than the more commonly taught $F=ma$). Furthermore, by introducing force and momentum together, the widely observed misconception that when a person throws a ball upwards the “force of the hand” acts on the ball even when it is in the air can be addressed in a way that makes sense to students [23]. Similarly, energy is only conserved if no work is done by a net external force. If work is done on a system by a net external force then its kinetic energy changes. These laws and concepts are typically covered in a number of chapters of an introductory physics book, usually in a way that does not make the links apparent to students. On the contrary, the many examples and end of chapter problems often make it difficult for students to distinguish between the handful of big ideas and key concepts and the numerous applications to specific situations. The hierarchical arrangement of ideas makes it easy to identify the small number of laws and concepts and how they are related, obviating the need to cover chapter after chapter of special cases and clearing the way for transfer of key ideas to other topics. In addition, according to cognitive science research, information that is “chunked” is much easier to store and retrieve than numerous disconnected pieces of information [24].

While the laws of physics are universal, they must be taught and learnt in specific contexts. The choice of context can affect students’ attitude to physics and their ability to do well in physics courses. Aspects of the contexts within which physics is taught appear to be one of the contributing factors to the low proportion of women who pursue physics degrees as opposed to other science degrees. Figure 4 shows that there is close to gender parity in biology, but this is far from true in physics. Concern about the low proportion of women physicists led the International Union of Pure and Applied Physics (IUPAP) to form the Working Group on Women in Physics in 1999, which has held international conferences every three years since 2002.

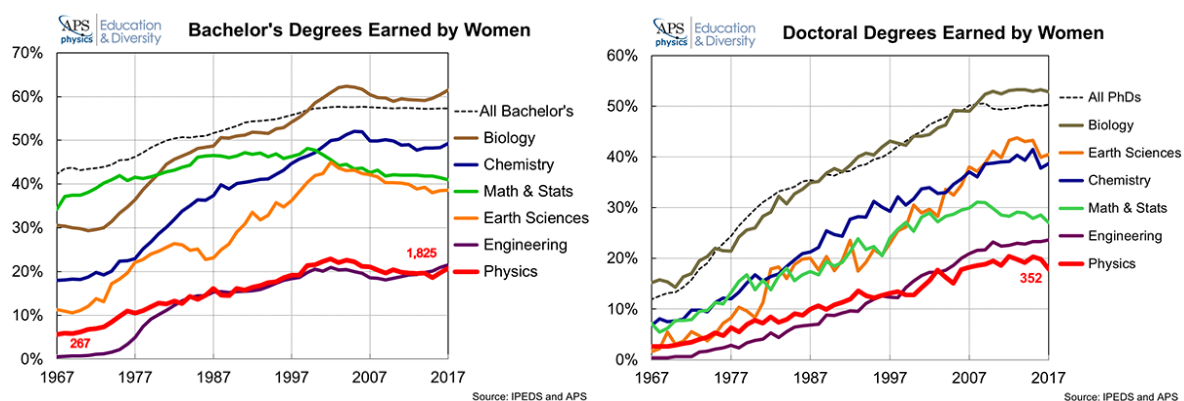


Figure 4. Percentage of bachelors and doctoral degrees awarded to women in various STEM subjects in the USA.

Of the many factors that deter women from becoming physicists, one is stereotyping. Physicists are typically portrayed as men, in textbooks, television, movies, interviews, and international awards. It was gratifying to see that one of the winners of the 2018 Nobel Prize in Physics was Donna Strickland, but she is only the third woman to win the prize in its 117-year history. Jocelyn Bell Burnell, the discoverer of pulsars, was not so fortunate, as the prize was given to her supervisor in 1974; she was, however, awarded the Special Breakthrough Prize in Fundamental Physics in 2018 [25]. When we teach the history of physics (which we should), we need to make reference to both women and men who made and are making important contributions to the field. There are a number of resources to help us do this [26].

We also need to make an effort to be inclusive in our representations of physicists, and of physics students, not only in terms of gender but also in terms of race and ethnicity. Figure 5 shows an example from a textbook of how this might be done.

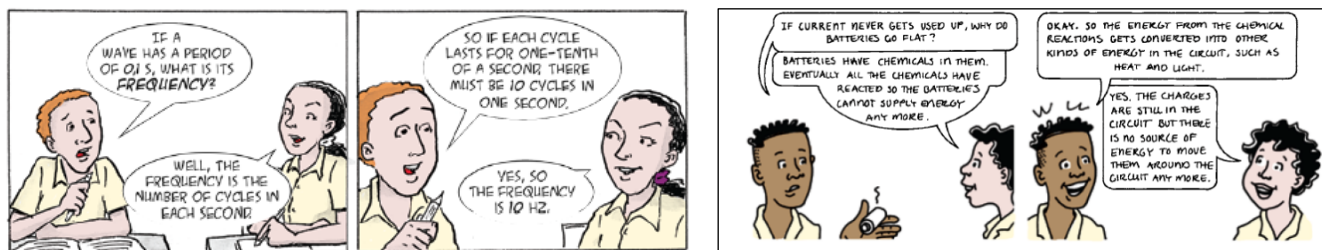


Figure 5. Cartoon strips from a Grade 10 textbook that show student diversity [27].

Stereotyping is also often evident in the kinds of activities and roles females are expected in undertake. Even for small children, toys are often colour-coded – pink for girls, blue for boys – and many of the “girls” toys reflect stereotypical gender roles associated with domestic life, while the “boys” toys encourage problem-solving, constructing objects and exploration. Even Lego, which was once gender-neutral, seems to be following this trend [28]. This early conditioning can easily carry over into the physics laboratory, with the result that when boys and girls work together in a group it is not unusual for the boys to manipulate the equipment and the girls to record the results, further disempowering girls and reinforcing stereotypical roles. The less hands-on experience the girls have, the less confident they feel and the more they avoid experimental work. This was certainly my own experience as an undergraduate; it was only once I was a teaching assistant that I began to develop confidence in my ability to use equipment. (It did not help that my high school teacher had told me that I would never be able to study physics at university because my laboratory skills were terrible!)

Stereotyping can lead to a phenomenon known as “stereotype threat”, “the experience of being in a situation where one faces judgment based on societal stereotypes about one’s group” [29]. Research has shown that experiences in which negative stereotypes are triggered can lead to lowered performance, while, conversely, efforts to neutralise stereotypes, such as indicating prior to a test that test results typically show no difference in performance between different groups, e.g. women and men or blacks and whites, can eradicate performance differences [30].

Research has also shown that mathematics and science teachers often treat boys and girls differently, for example, by giving boys more attention, more challenging interactions such as complex or open-ended questions, more eye contact, longer wait-times, more constructive feedback, calling on them more often and allowing them to dominate the classroom [31]. Conscious choices on the part of physics teachers to be even-handed in the roles and representations of females and males in the physics classroom, in the selection of examples and the attention and encouragement given to both can help all students to thrive.

Another important aspect of context is whether the application of physics is perceived as promoting harm or good. Fifty years ago many physics problems involved weapons – bullets, guns, even cannons (!). Perhaps this was understandable in the wake of the Second World War and the Cold War that followed it. Without entering into a debate about the need for weapons, numerous studies have shown that females tend to favour fields that are likely to benefit society (and the planet) over those that could harm it. In the case of girls who take physics at school, there is evidence that “More girls than boys report that they value social applications and want more social relevance in their physics courses,” and “girls predominate in the subgroup that study physics to do good and to help people. Students who study physics to do good tend to prefer physics content related to human aspects” [32]. Given the parlous state of the environment and the imperative for the people on this overpopulated planet to find ways to co-exist, it would be beneficial to select contexts in which physics is applied in ways that can help

humanity and the planet. Furthermore, if we are to help prepare our students for the 21st century world, we should link physics topics to global issues, both because they are part of the reality students will have to face and because they provide opportunities to develop creative problem-solving abilities and integrate what is learnt in various topics. A topic such as climate change provides enormous opportunities for students to apply a number of physics concepts and develop critical thinking skills, including learning to be critical about what they read on the internet and examine the trustworthiness of the sources of information.

The context in which physics is taught also needs to be meaningful to students in a particular time and place. Problems involving snow and ice will be perplexing for students who live in tropical climates; problems involving evaporative cooling as a means to stay cool in summer may be incomprehensible to students who experience very humid summers. While students should be exposed to more than their own immediate environment, it is important to try to use examples that are related to what students are familiar with, especially when concepts are first introduced. Figure 6 shows an example of how this could be done in Southern Africa, where traditionally many homes in rural areas have a thatch roof, which has excellent insulating properties, while people moving into cities or “modernising” may build homes with metal roofs. This example also provides other benefits in that it enables students to apply several thermal physics concepts at once, formulate a solution to an open-ended question and value indigenous knowledge.



Figure 6. Students are asked which roofing material will make the home more comfortable in a hot climate. (Values for specific heat capacity and thermal conductivity of thatch and galvanized iron are provided.)

Another important issue in how we should teach in the 21st century is how to incorporate technology appropriately. In the 1980s, when stand-alone personal computers were becoming widely available but before the world-wide web and internet connectivity were available to the general public, many people imagined that computers were the solution to key educational challenges. As I wrote in my dissertation in 1990 [33],

“There seems to be a widespread feeling that computers can significantly enhance instruction. This is evidenced by the fact that in recent years, substantial resources have been devoted to providing computer facilities to schools and colleges, both in the United States and abroad. Indeed, in many less well-developed nations, computers are more readily available than well-qualified teachers. Some administrators look to computers as the panacea for all educational woes.”

Now, in this internet age, there are still people who think that technology (not only computers but also other digital devices) is the solution to most educational challenges. There is no doubt that technology, if used wisely by teachers who understand how people learn, and particularly how students

learn their discipline, can be a useful tool to promote learning. But it is important to remember that technology is just that – a tool. Physics teachers therefore need to be clear about what the learning objectives are of their courses, and how best they can achieve them using a combination of pedagogical tools and approaches. Many universities now have learning management systems, also called virtual learning environments, in which teachers can upload learning resources, including video recordings of lectures, simulations, and links to interesting websites, and students and teachers can interact by means of online discussions. In the classroom, personal response devices or smartphone software can be used to poll students and then give the teacher immediate feedback on where he or she may need to spend time addressing conceptual difficulties. Certain experiments that are too expensive, too large or too dangerous to be done in a teaching laboratory can be viewed, interacted with or simulated. Wikis, blogspots and shared online writing tools can enable groups of students to work together on documents and projects. Online tutorial programmes, which are increasingly making use of learning analytics to tailor a programme to an individual student, can allow students to work at their own pace, spending more time on sections that they find more difficult than on others. Students’ computational skills can be developed by having them write their own simulations, animations or applications. These examples illustrate some of the ways in which technology can be incorporated into physics teaching, not as an end but as a means to enhance learning.

Another worthwhile teaching approach is to provide students with life-like or real-life applications. Authentic learning, problem and project-based learning are common in medicine and engineering, but much less so in physics courses. An example of how this can be done is an activity carried out at the University of Pretoria as part of the Additional Physics course for extended degree programme students in Engineering, just after the students had studied centre of mass. The activity was based on an approach to engineering education called CDIO (Conceive, Design, Implement, Operate), designed to better match engineering teaching to engineering practice [34]. The 275 students in the course were divided into six classes, and each class was divided into groups of 8-10 students. The classes met in normal classrooms for three 50-minute periods, and wrote up their reports afterwards. The task was to build a “skyscraper” out of extruded polystyrene and pencils on time and within budget that was as high as possible and could support a half litre bottle of water when tilted at 10° (showing it was “earthquake proof”). Each standard sized piece of polystyrene, each cut required to size it, each pencil and the “land” (size of the base) had an assigned cost. The assignments were marked using the criteria stability, height, budget, aesthetics, time, organisation and documentation. Figure 7 shows some of the students and their structures [35].



Figure 7. Engineering students’ “skyscrapers” withstanding the “earthquake proof” test.

In addition to the benefits of applying physics concepts to a life-like situation, the Skyscraper activity introduced students to some important real-world skills, such as completing a task on time and within budget. It also required students to work together to achieve a clearly defined goal and therefore develop collaborative skills, one of the important 21st century skills, in this case with diverse students.

Providing opportunities for students to collaborate is another useful teaching approach, particularly, as mentioned earlier, at a time when many of our students communicate with each other primarily via electronic means and not face-to-face. However, merely telling students to “work together” is not the same thing as collaborative learning. There are many approaches to collaborative learning, one of the most well-defined and thoroughly researched being cooperative learning. Johnson, Johnson and Smith have spent several decades exploring and developing the use of cooperative learning according to clearly articulated principles, and shown how, when these principles are followed, it can, “[increase student achievement, create positive relationships among students, and promote healthy student psychological adjustment to college” [36].

It is worth mentioning that with the wide availability of learning resources available through the internet on an anytime-anywhere basis, it is important to consider not only how we teach in formal learning spaces, but also what learning spaces are available to students outside of timetabled class time, both for individual and collaborative learning activities. Increasingly, universities are converting libraries and underutilised physical spaces, such as wide corridors and foyers, into informal learning spaces by providing furniture, ubiquitous Wi-Fi and, often, nearby access to food and beverages. This is helping to provide a seamless teaching, learning and socialising experience for today’s students.

5. Why teach physics in the 21st century?

“Fake news”, gender, racial, religious and ethnic discrimination, climate change denialism and other manifestations of the lack of education in critical thinking, logical reasoning and ethics are dangerous for the world. Perhaps more than ever before, education is vital for the survival of the human race and the protection of the planet. However, given the exponential growth in the complexity of tasks and the speed of execution that computers can carry out, it is important to be clear about the purposes of education in the 21st century. Hans Vestberg, CEO of Verizon Communications, suggests three important purposes for education in the light of the fourth industrial revolution [37]:

“As more computers equal or surpass human cognitive capacities, I see three broad purposes for education:

- Most obviously, to instil the quality STEM skills needed to adequately meet the needs of our ever-more-technological society;
- Just as importantly, to instil the civic and ethical understanding that will allow human beings to wield these powerful technologies with wisdom, perspective and due regard for the wellbeing of others;
- To find much more creative and compelling ways to meet these first two needs across a far wider range of ages and life situations than has traditionally been the case in our education systems.”

In this paper I have suggested that it is possible to achieve these purposes, at least in part, through physics teaching. A solid grounding in physics can:

- Equip students with an understanding of key physics concepts and principles that have enormous explanatory power and a wide range of applicability;
- Combat irrational and biased thinking, while promoting critical thinking;
- Inculcate ethics, pro-social values and open-mindedness;
- Develop creative problem-solving skills applicable to complex, real-world problems, such as addressing the UN Sustainable Development Goals [38].

The study of physics can play a vital role in developing graduates for the 21st century, provided we are cognisant of who our students are, how best to structure curricula that is relevant for the here and now, and what teaching approaches are most appropriate and effective for our students in the light of research on learning and the pedagogical tools available to us.

References

- [1] For authoritative reports see the website of the Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/index.htm> Accessed on 22 November 2018.
- [2] See, for example a media release from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services <https://www.ipbes.net/news/media-release-biodiversity-nature%E2%80%99s-contributions-continue-%C2%A0dangerous-decline-scientists-warn> Accessed on 22 November 2018.
- [3] http://www.wwf.eu/campaigns/living_planet_report_2018/ Accessed on 22 November 2018.
- [4] <https://news.nationalgeographic.com/2018/05/plastics-facts-infographics-ocean-pollution/> Accessed on 22 November 2018.
- [5] <https://www.theguardian.com/environment/2018/oct/22/microplastics-found-in-human-stools-for-the-first-time> Accessed on 22 November 2018.
- [6] <https://www.forbes.com/sites/bernardmarr/2018/05/21/how-much-data-do-we-create-every-day-the-mind-blowing-stats-everyone-should-read/#6a95a1de60ba> Accessed on 22 November 2018.
- [7] <https://publications.parliament.uk/pa/cm201719/cmselect/cmcmds/363/363.pdf> Accessed on 22 November 2018.
- [8] David Bohm 1996 *On Dialogue*. London: Routledge.
- [9] Klaus Schwab, Founder and Executive Chairman, World Economic Forum, 14 Jan 2016. <https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/> Accessed on 22 November 2018.
- [10] <http://time.com/247/millennials-the-me-me-me-generation> Accessed on 22 November 2018.
- [11] Rosen, L D, Whaling, K, Rab, S, Carrier, L M and Cheever, N A 2013. Is Facebook creating “iDisorders”? The link between clinical symptoms of psychiatric disorders and technology use, attitudes and anxiety. *Computers in Human Behavior* **29** (3) 1243-1254.
- [12] <https://childmind.org/article/how-using-social-media-affects-teenagers/> Accessed on 5 December 2018
- [13] https://www.ikea.com/ms/en_US/service-offer/assembly.html Accessed on 5 December 2018
- [14] <https://www.forbes.com/sites/neilhowe/2014/07/02/millennials-struggle-to-pass-life-skills-101/#d0070e879e71> Accessed on 5 December 2018
- [15] Rideout, V, Robb, M B 2018. *Social media, social life: Teens reveal their experiences*. San Francisco, CA: Common Sense Media.
- [16] <https://www.johnshopkinshealthreview.com/issues/fall-winter-2017/articles/the-rise-of-teen-depression> Accessed on 12 December 2018.
- [17] https://www.bcbs.com/sites/default/files/file-attachments/health-of-america-report/HoA_Major_Depression_Report.pdf Accessed on 12 December 2018.
- [18] <https://www.psychom.net/depression-teens-social-media> Accessed on 12 December 2018.
- [19] https://web.phys.ksu.edu/icpe/Conferences/ICPE2004_proceedings.pdf Accessed on 22 November 2018.
- [20] Grayson, D February 2006. Rethinking the content of physics courses. *Physics Today* **59** (2).
- [21] Centre for the New Economy and Society 2018 *The Future of Jobs Report 2018*. Geneva, Switzerland: World Economic Forum.
- [22] Arons, A 1990 *A Guide to Introductory Physics Teaching*. New York: Wiley & Sons
- [23] Grayson, D J 2004 Concept substitution: A teaching strategy for helping students disentangle related physics concepts. *American Journal of Physics* **72** (8), 1126-1133.

- [24] Bransford, J D, Brown, A L and Cocking, R R (eds) 1999 *How People Learn. Brain, Mind, Experience and School*. Washington, D C: National Academy Press, 20-21.
- [25] <https://www.smithsonianmag.com/smart-news/decades-after-being-passed-over-nobel-jocelyn-bell-burnell-gets-her-due-180970248/>
- [26] See, for example, <https://www.amightygirl.com/>, <https://500womenscientists.org/>, and Nina Byers and Gary Williams (Eds) 2006 *Out of the Shadow: Contributions of Twentieth-Century Women to Physics*, Cambridge University Press.
- [27] Grayson, D, Harris, McKenzie, J & Schreuder, B 2011. *Platinum Physical Sciences Grade 10*. Cape Town, South Africa: Maskew Miller Longman.
- [28] <https://www.bustle.com/articles/13010-girl-toys-have-gotten-a-whole-lot-girlier-since-your-1980s-or-1990s-childhood> Accessed 5 December 2018.
- [29] Directorate-General for Research and Innovation 2012. *Meta-analysis of gender and science research. Synthesis report*. Brussels: European Commission.
- [30] <https://journals.aps.org/prper/collections/gender-in-physics> Accessed 28 December 2018.
- [31] Sagebiel, F and Vázquez-Cupeiro, S (2010). Stereotypes and identity. Meta-analysis of gender and science research – Topic report 2010.
http://genderinnovations.stanford.edu/images/TR3_Stereotypes.pdf
- [32] Murphy, P and Whitelegg, E 2006 *Girls in the physics classroom: a review of the research on the participation of girls in physics*. London, UK: Institute of Physics.
- [33] Grayson, D J (1990) *Use of the Computer for Research on Instruction and Student Understanding in Physics*. PhD dissertation. University of Washington, Seattle.
- [34] www.cdio.org/benefits-cdio Accessed on 28 December 2018.
- [35] <http://cdio.org/knowledge-library/documents/extended-degree-programme-students%E2%80%99-experiences-skyscraper-activity> Accessed on 28 December 2018.
- [36] Johnson, D W, Johnson, R T and Smith, K A 1998 *Active Learning: Cooperation in the College Classroom*. University of Minnesota. DOI: 10.5926/arepj1962.47.0_29
- [37] <https://europeansting.com/2018/09/24/why-we-need-both-science-and-humanities-for-a-fourth-industrial-revolution-education/> Accessed on 29 December 2018.
- [38] <http://www.un.org/sustainabledevelopment/sustainable-development-goals/#prettyPhoto> Accessed on 29 December 2018.