PISA 2024
Strategic Vision and Direction for Science

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PISA 2024 Strategic Vision and Direction for Science: A Vision for What Young People Should Know About Science and be Able to Do with Science in the Future

1. The PISA 2024 Core 2 contract called for a Strategic Visioning Phase (SVP) within the framework development activities to provide a steering document to inform discussion and prioritisation by the Pisa Governing Board (PGB), prior to the Science Framework that will be developed in the next phase by the Science Expert Group (SEG). The methodology used during the SVP is described in Appendix 1 and central to the creation of this paper has been the formation of the Strategic Visioning Expert Group (SVEG). The Strategic Visioning Expert Group proposes that the PISA Science Framework could be significantly updated through the introduction of three new content/knowledge areas, two new competencies and a new dimension with sub-dimensions.

Context

2. Science education has the capacity to help support and equip young people with the knowledge, skills and identities (agency, attitudes, experiences, and personal and social resources, such as resilience) that will enable them, their communities and societies to tackle many challenges in the next decades. The extent to which young people are able to critically engage with and use scientific knowledge and competencies in their lives beyond the classroom will be important not only for them personally, but also for the health, fairness and prosperity of societies globally.

3. This document sets out a vision for the additional knowledge, competency and identity outcomes that a young person in 2024 and beyond would be expected to acquire from their science learning experiences in order to provide a valuable foundation for future life. The vision is based on the principle that scientific knowledge and competencies are important and valuable for young people's futures, but that identity outcomes (and the extent to which young people feel meaningfully connected to science, as critical consumers and producers of science in their daily lives) are also crucial for supporting agency and active citizenship in a rapidly changing world.

4. The PISA 2024 vision survey (described in Appendix 1 and 2) demonstrated that there is a wide, and internationally consistent, awareness of factors in the science domain that will affect the world that young people emerge into in 10-15 years' time.

5. The SVEG has identified three key dimensions that describe what should be achieved by all 15-year-olds: Scientific Knowledge; Scientific Competencies; and Scientific Identity. The first two dimensions are already part of the PISA Science framework, but the latter is an addition.

Scientific knowledge

Adding Three New Knowledge Areas

6. The SVEG view is that the scientific knowledge young people will need should be reorganised and updated to better equip them for the world they will live in. The recommendations are for the creation of three new knowledge areas:

- **'Socio-environmental Systems and Sustainability',** to support young people in solving complex, interconnected problems relating to issues which will impact them. This area will include some knowledge previously encompassed within the disciplinary subject areas.
- **'The Development of Scientific knowledge and its Misuse'**, to give students a better appreciation of how knowledge is developed, and help them navigate the incorrect use of knowledge such as in climate change denial or the anti-vaccination movement.
- **'Informatics',** to emphasize the importance of the study of data, and the structure and behaviour of information processing systems, both for their impact on society through digital technology, in particular, Artificial Intelligence (AI), and for their role in helping the advancement of knowledge in all scientific domains through computational models (for example, in genomics).

Rationale

7. During the visioning process, the SVEG felt it important to consider the knowledge young people will need in the future. The SVEG identified a need to reconsider both the content and its organisation in order to better suit the future needs and the aspirations of young people. The current organisation of knowledge within PISA Science is mostly based on a very traditional disciplinary framework, and lacks the cross-cutting, contextual, and interdisciplinary approaches necessary to help in the understanding and solving of problems. Furthermore, although contemporary challenges demand the use of scientific knowledge in a broader context (Erduran and Dagher, 2014), current approaches to the teaching of science do not show how scientific knowledge develops over time.

8. The SVEG considered the existing areas and felt that there was a need to expand the areas of knowledge to place more emphasis on the cross-disciplinary nature of science. It was also thought necessary to recognize the fact that science is used within a social and environmental context that involves consideration of economics, social behaviour, and ethics. Hence the SVEG proposes to add a new knowledge area in order to address what are perceived to be deficiencies in the light of the current challenges faced by humanity – "Socio-Environmental Systems and Sustainability". It was felt that this would better represent the complexity and interconnection of problems young people will face in their lifetime, such as climate change, pandemics, food security.

9. Young people need to be critical consumers of scientific knowledge in an era where it is so readily accessible and where arguments may be based on unreliable or questionable science. They must have some understanding of the way in which science develops reliable knowledge through historical or contemporary examples. Such insight can potentially help

students scrutinise the misuse of science in contemporary themes such as climate change denial, pseudoscience and fake news.

10. Rapid advancements in computer-based systems and automation, as well as the availability of huge sets of digital data are having a notable impact on our societies and economies, and have transformed how scientific knowledge is acquired and used. Having been designed on scientific concepts, theories, principles, and methods, these technologies will continue to improve our knowledge of the world, while becoming an ever-present part of young people's personal and professional lives. Fluency in the study, interpretation and usage of data, and the structure and behaviour of digital systems carrying out automated processings of representations will provide young people with a good foundation for their future in an increasingly digital world.

Socio-Environmental Systems and Sustainability

11. Science is a powerful tool that humans possess for understanding the material world. Once we understand problems, science gives us ways to solve them, for the benefit of all. The SVEG believes that an approach to defining content knowledge that focuses on people, their needs and interactions with the natural and physical worlds, rather than the internal organisation of scientific facts, is desirable because such an approach will resonate more strongly with young people who seek to see the relevance of science to their lives. Solving real-world scientific problems requires interdisciplinary approaches and methods that focus on the system and its social, environmental and physical interactions (Clark and Dickson, 2003). Accordingly, the SVEG suggests the addition of a new integrated area of knowledge and a rearrangement of those pre-existing areas in the 2015 Framework, to be called: Systems and Sustainability.

12. The growing recognition that understanding and acting upon many of the problems the world faces today cannot happen from a disciplinary perspective has fostered the emergence of new areas of knowledge that integrate across the natural, social and engineering sciences (Clark and Dickson, 2003; Kates et al. 2001). These include, for example, Sustainability Science, Complex Systems and Political Ecology. Many of these new areas seek also to integrate with the practical world by intentionally and actively seeking to solve problems by co-creating knowledge with practitioners, stakeholders and policy-makers. Early introduction and exposure of students to these new ways of thinking and acting to solve socio-environmental problems such as climate change, pandemics, water security and conservation of species is paramount to prepare them for an uncertain future that can critically shape their well-being. Such systems could include:

- Economics, markets, institutions
- Population, migration, well-being
- Ecosystems, natural resources, conservation
- Climate change, mitigation and adaptation
- Sustainable food systems, nutrition, food security
- Health, environmental health, pollution and spread of disease
- Land use and change
- Water, governance and water security
- Energy supply, development of renewables, and retirement of carbon-based energy resources.

13. Such knowledge would equip young people with the ability to identify elements of a complex system and to recognise the interactions within a system, as well as between systems. For instance, the reintroduction of wolves into any ecosystem has consequences for the local environment that includes the plants, trees and flow of water in the system. To fully evaluate such initiatives requires asking broader questions than just what might be the immediate impact on farmers or the deer population, for example.

The Development of Scientific Knowledge and its Misuse

14. Young people should have some appreciation of the intellectual achievement that our contemporary scientific understanding represents. This applies not only to knowledge for which there is current consensus (e.g. structure of DNA) but the errors and flaws that have been made in the past – for instance, the geocentric world view, Lamarckianism, caloric theory, cold fusion, eugenics. If one of the goals of science is to 'teach how science works' (OECD, 2009), then it is equally important to teach students how science *does not* work (Allchin, 2012). Studying science in a historical or contemporary context exposes how scientific knowledge develops and the community practices (e.g. peer review) and criteria (e.g. objectivity) that enable it to establish reliable knowledge (Matthews, 2015). The inclusion of some selected case studies from science's history (including the recent history of science) can help students identify the flaws in the scientific arguments of those who wish to discredit the use of vaccination, deny the existence of anthropogenic climate change or argue for a creationist worldview.

15. Another important issue from recent history of science is the commercialisation of scientific knowledge in the context of new domains such as gene technology (Erduran and Mugaloglu, 2013). Technology and innovation are paving the way for new profit opportunities around scientific knowledge. Scientific knowledge is increasingly commodified within a science market that treats information as private property. Commodification of scientific knowledge may potentially hinder free consumption of scientific knowledge by the public (including teachers and students) or rival producers of scientific knowledge among scientists. Trends in the commercialisation of scientific knowledge point to the need to equip students with understanding of how economic and political factors may influence decision-making about scientific knowledge (e.g. patenting of genes).

Informatics

16. Informatics is the study of the data, structure, and behaviour of natural and computational systems. The SVEG is proposing Informatics is considered for inclusion within the Science Framework, either as an additional knowledge area, or integrated within the existing and proposed additional knowledge areas.

17. Artificial Intelligence (AI) and machine learning are branches of informatics that are having a significant impact on our societies and economies. The fundamentals of AI are based on designing systems which mimic or emulate systems found in nature, and a basic knowledge of natural data structures and systems is therefore beneficial in developing a conceptual understanding of how AI works and can be developed.

18. Besides its applications in AI development, informatics also plays an important role in acquiring and using knowledge across the scientific disciplines. Biological and health sciences, in particular, have seen rapid advancement in recent years, with bioinformatics and genomics now holding the key to solving many of the world's problems. In the future, when personalised medicine will become standard practice, all healthcare practitioners and indeed patients will

need to possess the knowledge and competencies to decode the information obtained via genome sequencing and testing.

19. With this in mind, the SVEG believes that every young person should be digitally and data literate at age 15. This includes being familiar with different models for the representation of data, basic computational models and algorithms, as well as any additional areas of procedural knowledge resulting from ‘dry lab experiments’ (involving large data sets and information structures). Moreover, being digitally and data literate would enable young people to understand AI concepts and computational systems at a basic level in order to make important decisions about how to act on information presented to them. It would also support them in functioning and succeeding in transformed workplaces, allowing them to be active participants in the digital world. Ultimately, such knowledge will support young people to understand, use, participate in, influence, and contribute to the development of both the digital world and a fair, just and safe digital society (Caspersen et al. 2019; Nardelli 2019).

20. Appendix 3 further defines the discipline of informatics, and the knowledge and competencies it comprises. It also explains how this new domain is different from computational thinking (as defined in the PISA Mathematics Framework).

Scientific Competencies

Adding Two New Competencies and Developing Two Existing Competencies

21. Given the technological advancements over the past decade, the scientific competencies required by young people to thrive in society will need to be further developed.

22. The view of the SVEG is that two new competencies should be developed, and two existing competencies expanded. The two new competencies are:

- **Using scientific knowledge for decision-making and action,** as young people need the capacity to actively use their scientific knowledge to decide on courses of action, and to create new value. These decisions need to be made in complex systems, taking into account economic, political, and ethical considerations.

- **Using probabilistic thinking,** as understanding probability and risk are central to most scientific issues and essential for informed decision-making.

The two competencies to be expanded are:

- **Evaluating and designing scientific enquiry,** to add the ability to research information and design enquiry within complex systems.
- **Interpreting data and evidence scientifically**, to add the ability to interrogate large data sets, as well as the ability to use scientific judgements for decision- making.

Rationale

23. Science education is playing an increasingly important role in providing young people with the crucial thinking tools needed to navigate a non-stop world characterised by information deluge, new physical technologies and new AI capabilities. How these characteristics will impact the world in the future is yet to be determined, but science, through its specific methods and culture, can equip young people with the competencies needed to critically examine them and responsibly engage with what they offer.

24. The PISA 2015 Science framework already identified three key competencies, and it is the view of the SVEG that the existing competencies (explaining phenomena scientifically; evaluating and designing scientific enquiry; interpreting data and evidence scientifically) need to be both extended and complemented by new ones, especially as new technologies have played increasingly visible roles in our societies' deliberation and decision-making.

25. The two new competencies that need to be added are:

- Using scientific knowledge for decision-making and action, as most of the dilemmas that will confront individuals in their personal and professional lives can be informed to some degree by scientific findings.

- Using probabilistic thinking, as understanding probability and risk is a central feature of most scientific issues confronting citizens in today's society.

Using scientific knowledge for decision-making and action

26. The SVEG recognizes that scientific knowledge has an intrinsic value for understanding the material world in which we live and is of the view that young people in the future should be able to:

Use scientific knowledge for decision-making

27. One of the major goals of science is to produce findings that can inform and improve action. Most of the dilemmas that confront individuals in their personal and professional lives can be informed to some degree by scientific findings. Appreciating how science has contributed – and can contribute – to the improvement of health, energy and food supply, and adaptability to climate change are all important outcomes for any science education. More broadly, developing the ability to investigate how science might inform an issue, whether personal, local or global, and asking appropriate questions, will help young people to see the relevance and salience of science.

28. Thus young people need to be able to consider the different mechanisms that result in particular events and the extent to which these are caused by scientific, social, economic and political dimensions (Levinson, 2018). By explaining the world using this interdisciplinary approach young people are better able to operate within complex systems, to identify the best solutions to problems by evaluating their relative strengths and weaknesses, and to evaluate different courses of action on the basis of ethical and economic advantages and disadvantages. Moreover, they are also better able to identify the physical, ecological and socio-political feedback mechanisms and behaviours that occur because of the connections within a system.

Take into account ethical considerations

29. Advancements in technology, in particular artificial intelligence and biotechnology, add layers of complexity to decision-making. Science education plays a key role in ensuring young people are equipped to apply ethical reasoning in relation to science, to consider consequences and evaluate externality in relation to experimental design and problem analysis. They will also need to accept that science does not give direct answers for decision-making or about 'what one should do', but requires an ethical and value-driven component that is strongly linked with issues of identity and inequalities. Finally, young people will need to ask themselves if their actions, or actions of others who they enable or support, are ethical and in-line with their values, and apply this thinking and their values consistently in their everyday lives.

Create new value through problem-solving and innovation

30. Science education needs not only to equip young people with decision-making competencies to navigate life, but also to empower and support them to develop competencies involved in taking action and 'creating new value'. This transformative competency is essential for acting towards improving our society. When young people create new value, they ask questions, collaborate, and try to 'think outside the box'. They approach problems using a range of strategies, reflect on what has and has not worked, and have the resilience and agility to try again in search of a solution. In doing so they can become more prepared and resilient when confronted with uncertainty and change.

31. Problem-solving and innovation are fundamental features of science yet, too often, these do not feature in a young person's experience of science at school. When young people's decision-making and agency are encouraged, more positive attitudes towards science and stronger identification with science are supported.

Using probabilistic thinking

32. The SVEG is of the view that understanding probability, uncertainty, and risk is a central feature of most scientific issues confronting us all, young and old (Bennet and Calman, 2000; Adams, 1995). It is, for instance, central to understanding how to respond both personally and as a society to the challenges posed by global health emergencies, such as a pandemic. At the core of all risk judgments is an understanding of probability, normal and abnormal distributions and the meaning of common ways of expressing uncertainty, so young people in the future will need to be able to:

Recognize and utilize the power of probabilistic assertions, a key element of scientific culture

33. Scientists treat essentially every proposition and every statement of possible fact with some degree of tentativeness, whether 51% confidence (only just more likely to be true than false) or 99.9999% confidence (high certainty to be true). Using this pervasive probabilistic thinking approach makes it possible for scientists to be more comfortable with being wrong, on the one hand, and with changing their position with respect to new evidence, on the other. Young people should be able recognise this usage as a source of science's strength, not an indication of weakness. They should also be able to estimate the confidence level associated with their own statements in an argumentation or discussion.

Interpret levels of confidence in a claim

34. All scientific measurements have some errors associated with them. Thus, the simple binary distinction of true/not true is not valid when dealing with complex, multivariate systems. Young people should be able to estimate what fraction of scientific papers that make a claim with 95% confidence could turn out to be wrong. For instance, they should understand why they should treat one newspaper article about health-related issues with a degree of scepticism, and understand that progress in knowledge is built through an accumulation of similar findings which gradually increase our confidence and certainty. More generally, they should be able to recognise the limitations of scientific inquiry and apply critical thinking when engaging with its results.

Recognise that all activities have risk associated with them, and be able to interpret risk statistics and their implications

35. Furthermore, all activities have risks associated with them. Risk statistics commonly only measure fatalities and not injuries and the decision to take risks is different depending on whether it is an individual risk, a population risk, a system risk or a lifetime versus immediate risk. Students need to understand that risk is an inherent feature of life and not something to be avoided.

Recognize the common forms of representing population statistics, their use and misuse

36. Students need to understand the concept of a normal distribution and the difference between a mean and a median. They should also understand that confidence is commonly

expressed with the use of an error bar, and that within any population there will be variability and outliers. Using this knowledge, they should be able to make evaluative judgements of statistical data asking, for instance, what meaning can be attached to the outliers. For instance, they should be able to distinguish between cause and correlation and be aware that within any large data set there is a high chance of seeing what appear to be significant effects. The latter is particularly important given the increasing use of large data sets and the possibility for misinterpretation or bias due to the nature of the underlying data. Students should be able to say that if two data points are within each other's error bars they represent effectively the same level, even if one is apparently higher than the other; and therefore it is impossible to compare two data points if their error bars are not given.

Make predictions

37. Increasingly students will be living in a world where large data sets and machine learning algorithms are used to make predictions. Students need to be able to interrogate the predictions or findings made by such AI systems by asking whether the data set used is biased, and by questioning the size of the data set on which it is based and the level of confidence that can be placed in the predictions.

38. The two existing competencies to which additions are suggested are:

- Evaluating and designing scientific enquiry
- Interpreting data and evidence scientifically.

Additions to the competency of "Evaluating and designing scientific enquiry"

39. The SVEG also considered the existing competency of "Evaluating and designing scientific enquiry" and felt that it needed to be expanded to include two additional elements.

Understanding design in complex systems

40. Observing and understanding systems, at both a micro and a macro level, allows for identification of emerging phenomena, physical reactions and behaviours. Understanding complexity allows for identification of emerging properties that can sometimes only become apparent when moving between a system's levels.

41. By being able to understand design in complex systems, young people will be able to:

- Identify the elements of a complex system
- Recognise what component subsystems are and how they interact with each other (sources and sinks; feedback loops; levels of organisation)
- Predict the impact of action within a system
- Predict the impact of action of a system on another
- Make risk assessments within the context of a system.

Researching and evaluating information

42. All enquiry begins on a base of existing knowledge. Increasingly such knowledge is provided by search engines. Thus, young people need to be able to evaluate scientific searches in a critical manner by recognizing potential biases and unreliable sources or untrustworthy resources (Breakstone, J., et al. 2018). For instance, young people should:

- recognize that multiple searches may be necessary using different terms and requiring them to then identify the best and most relevant resources to their inquiry.
- look for **e**vidence that there was some consideration of the ways that the findings may be flawed or limited and/or evidence of an understanding of the complexities of the topic.
- make evaluative judgements about the expertise of the source.

43. To do this, young people will need to be able to identify the essential elements of an argument distinguishing between a claim, its supporting evidence and the reasoning that supports the argument. They should be aware of the issue of confirmation bias and look to see whether counter arguments have been considered and addressed and use this information to help them make evaluative judgements of the quality of the scientific work and the validity of the claims. Key tests would be whether they can identify pseudo science, fraudulent science and poorly done science from good science that happens to get the wrong answer.

Additions to the competency of "Interpreting data and evidence scientifically"

44. Technological tools increasingly offer young people the ability to interrogate large data sets. Young people need to be able to distinguish between the value of searches which are based on scientific hypotheses and activities which are essentially looking for patterns providing a rationale for the search they are undertaking. They should be alert to the fact that in most large data sets such patterns may be the product of randomness, spurious correlations. Only rarely do the patterns reveal an underlying causal relationship which needs to be advanced (Calude, C.S. et al. 2017).

45. Young people need to have the competency to use basic data tools which enable the interrogation of such data sets and generate meaningful representations of the data in standard forms such as histograms, graphs or stem and leaf plots.

46. In addition, an important element of evaluating data is the ability to make order of magnitude estimates of quantities to see if a finding fits within the bounds of rational, common sense possibility. Such data is used to make judgements and contributes to the new competency of using scientific knowledge for decision-making and action. Hence the existing competency might be more aptly renamed as "Interpreting data and evidence to make judgements"

Scientific Identity - a New Dimension in the PISA assessment

Adding a new dimension to the PISA Science Framework

47. It is the view of the SVEG that identity is a key factor shaping the extent to which scientific knowledge and competencies can be both achieved and realised. Identity mediates learning and understanding – if we fail to pay attention to a young person's scientific identity outcomes then we undermine the achievement and potential of scientific learning and the extent to which young people will be able to critically use and act with these competencies in life. Identity outcomes are integrally tied to social justice and are key considerations when working towards more equitable science cultures and practices. Key scientific identity outcomes include young people achieving a meaningful connection with science, feeling that science is 'for me', finding science to be useful and relevant to their everyday life, experiencing science as valuing and inclusive of diverse people and experiences and using science to challenge social and environmental inequalities.

48. We propose this new dimension to sit alongside the knowledge and competencies dimensions of the PISA science literacy framework – although there may be a case for some elements to be captured within the contextual questionnaire. The scientific identity dimension would capture the extent to which, by 15 years old, a young person has developed:

- **Science Capital,** a holistic measure of young people's scientific identity, attitudes towards science, behaviours and contacts, culminating in a feeling of science being 'for them'.
- **Critical science agency,** the capacity to critically use science and other forms of expertise to personal and social benefit, particularly to address social inequalities.
- **Inclusive science experiences and practices,** encountering diverse and inclusive learning experiences and representations of science.
- **Ethics and values,** experience and understanding of science as an ethics and value-based practice that relates as much to identity as to knowledge and understanding.

Rationale

49. The science identity dimension represents a new, bold area for science education and PISA to consider. It is grounded in extensive research evidence (collected and reviewed as part of the inquiry, e.g.; Archer et al., 2010; Calabrese Barton and Tan, 2019; Carlone et al., 2014; Danielsson, 2009; Pea, 1993; Barron, 2006; Nardi and O'Day, 1999; Letham, 2007; Dweck, 1988). As detailed below, the science identity dimension includes, but crucially is also much more than, 'attitudes to science'. Identity is fundamental to science learning and attainment and should be considered at the same level of significance as knowledge and competencies.

50. It is the view of the SVEG that the scientific identity dimension should be considered as an important and urgent priority within a contemporary vision of what we should expect a

young person to have achieved by age 15 as a result of their science learning. This is because: (i) the learning sciences literature has demonstrated that identity is key to science learning, attainment and participation (e.g. Nasir and Hand, 2008; Shanahan, 2009; Dweck, 1988; Barron, 2006; Nardi and O'Day, 1999);

(ii) scientific identity is integral to, but also distinct from, scientific knowledge and competencies, shaping the extent to which students think about, learn, understand and engage (or not) with science;

(iii) this dimension brings issues of ethics, equity, inclusion and power to the fore – it provides a strong link and grounding to issues of equity and inclusion and can indicate the equitable 'health' of a learning ecosystem. Issues of equity are essential to a contemporary vision of what science education outcomes should be and how science and science education should be practised. Equity and identity issues are also important when considering the large scale future employability of this generation of learners;

(iv) identity provides a means to situate learning – that is, to link with the Learning Ecology, which together enable (or constrain) the possibilities for learning and attainment. A learning ecology is defined by students, peers, teachers and parents/social influences. The attitudes and beliefs of this ecology of influences underpins independent learning and attainment;

(v) issues of identity and equity impact substantially on young people's ability to participate meaningfully in society and the future of work requires that young people are able to enjoy, participate in and shape responsible research and innovation. A goal of science learning should be to enable all young people to feel meaningfully connected with science and to be critical users and producers of science.

51. The SVEG proposes that this dimension needs to be valued as a core dimension within a contemporary vision of young people's scientific preparation for the future (and hence should primarily be included as part of the cognitive assessment) because:

- The identity dimension has been historically missed in summative assessment, resulting in narrow framing of the goals of science learning.
- Narrow framings can translate into educational practices that result in low science engagement, limited science learning transfer between classes, grades, schools and adult life and work and inequitable learning cultures (as 'what gets measured gets valued'). It is thus important to reflect on the extent to which global assessment instruments might either exacerbate or ameliorate effective and equitable science teaching and learning.
- A more holistic assessment tool might help work towards disrupting pernicious practices associated with high-stakes assessment, such as 'teaching to the test' and exclusion/neglect of equity concerns. It could help support more productive and equitable pedagogies in science education.

52. Although thi***s*** is a 'new' dimension for PISA to consider, there are useful and usable (valid and reliable) existing measures (Archer et al., 2015) that can be drawn upon for translation into assessment frameworks.

Science Capital

53. ‘Science capital’ (Archer et al., 2015) refers to a person’s science-related resources, including their science attitudes, understanding (scientific literacies and competencies), identification with science, behaviours and social contacts. Extensive evidence has shown that science capital plays a key role in shaping the extent to which a young person experiences science as being ‘for me’, or not, and significantly relates to post-16 science aspirations and progression (Moote and Archer, 2020a; Moote et al., 2020b; Moote et al., 2019). It has also been found to relate to attitudes and aspirations in engineering, mathematics and technology.

54. Science capital is a composite measure that includes a number of dimensions that have been extensively tested and developed into valid and reliable measures through a range of international studies.

55. Research demonstrates that student science capital can be ‘built’ (supported and developed) through appropriate science classroom pedagogy (Archer et al., 2017; Godec et al., 2018; Godec et al., 2017).

56. Elements of science capital that it would be desirable for young people to have developed by age 15 would include:

- A feeling that science is ‘for me’ (e.g. seeing science as relevant, meaningful and useful for their own current and future lives)
- Having been substantially recognised, encouraged and supported by significant others (e.g. teachers, carers) in their identification with science
- Understanding of transferability of science knowledge and competencies for current and future life and work (beyond, not just in, science-related areas)
- Engagement with science in their own lives beyond the classroom, including being critical consumers and producers of science and using science for personal/social benefit
- Possessing science-related social capital (e.g. science-related social networks, knowing and having met diverse ‘science people’).

Critical Science Agency

57. **‘Critical Science Agency’** refers to “using science knowledge and other forms of distributed expertise to redress instances of injustice” (Schenkel et al., 2019a). The concept has been developed through extensive empirical research, notably studies conducted with young people from communities historically under-represented in science (Schenkel and Calabrese Barrton, 2020; Schenkel et al., 2019b). Evidence shows that supporting and enabling young people’s critical science agency has a range of significant benefits for young people and their communities and supports more equitable and inclusive STEM pedagogy.

58. Critical science agency relates to the ‘using scientific knowledge for decision-making and action’ competency, but also extends beyond this competency through (i) the explicit social justice framing and foregrounding of issues of power and equity, (ii) the integration and valuing of wider forms of community knowledge and expertise alongside canonical scientific knowledge and (iii) the role of critical science agency in re-shaping prototypical and normative

science (e.g. young people using critical science agency to make science practices and normative ways of knowing more equitable and inclusive).

59. Elements of critical science agency that it would be highly desirable to achieve among young people include:

- Young people reporting that they are using and creating value from their science learning experiences in a wide range of ways, but particularly for challenging societal social and environmental inequalities
- Students having experienced using science in their lives to take action on issues that matter/are meaningful for them and their communities and recognising how they can be part of 'solutions', both individually and collectively
- Capacity to be critical consumers and producers of science
- Feeling that their identities and cultural knowledges and experiences are valued and respected within science
- Understanding of the role of science within contemporary and historical injustices and how this is being and can be challenged
- Be able to use science as a part of their intellectual toolkit.

Inclusive science experiences and practices

60. A successful science education should be addressing and closing 'gaps'[1] (not creating and exacerbating inequalities) between different social groups (e.g. by race, class, gender, sexual orientation, religion, disability, ethnicity, etc.) in terms of their science knowledge, competencies and identity. Young people from all backgrounds need to be able to feel as though science 'is for them'. A successful, high performing system would be judged as one that is actively and urgently changing and improving patterns of attainment, agency and inclusion. In addition to a lack of socially patterned outcomes by critical science agency and science capital, further successful outcomes could include all students:

- Having the (pedagogical, material, social and digital) resources, opportunities, contexts and experiences to enable them to effectively learn and do well in science
- Experiencing inclusive science learning environments
- Encountering broad and diverse representations of science and scientists as part of their normal, everyday science teaching and learning
- Feeling safe, respected, valued and included in science.

[1] The term 'gap' is used here with caution. While it is broadly used and understood within education policy, it is also highly contentious because the term reifies achievement differences and hides the causes of these differences through a deficit framing. A more useful term is Ladson-Billings'(2006) notion of the education 'debt', which explains the cumulative impact of unequal resources and injustices that create differences between privileged students and those from minoritized communities (e.g. students of colour, students from low-income communities, etc.).

Ethics and Values

61. This area relates to aspects of Competencies (e.g. Understanding limitations and Using scientific knowledge for decision-making and action) but brings the dimension of ethics and values more explicitly to the fore.

62. The practice of science cannot be divorced from ethics and values. An understanding of ethics and social values specifically in relation to science (knowledge, methods, practices and outcomes) should be an important outcome for all 15-year-olds.

Final Thoughts

63. Science education has the capacity to help support and equip young people with the knowledge, skills and identities that will enable them, their communities and societies to tackle many challenges in the next decades. The extent to which young people are able to critically engage with and use scientific knowledge and competencies in their lives beyond the classroom will be important not only for them personally, but also for the health, fairness and prosperity of societies globally.

64. The qualitative survey (described in Appendix 1 and 2) demonstrated that there is a wide, and internationally consistent, awareness of factors in the science domain that will affect the world that young people emerge into in 10-15 years' time. Analysing, probing and debating these factors gave the SVEG material to blend with their knowledge, expertise and research output, to create the vision in this document.

65. The SVEG proposes that the PISA Science Framework could be significantly updated through the expansion of two existing competencies, and the introduction of three new knowledge areas, the introduction of two new competencies and the introduction of a new dimension with sub-dimensions. Whilst this represents a bold and ambitious proposal for the PISA science assessment, it is driven by the current innovations in the field of science and the growing social and environmental aspects affecting young people.

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Appendix 1 - Strategic Visioning Phase Methodology

66. This appendix describes the Strategic Visioning Phase (SVP) of the PISA 2024 Framework development and constitutes Deliverable E of the PISA 2024 Core 2 contract. Two advisory groups were established: the Strategic Visioning Expert Group (SVEG), and the Science Advisory Panel (SAP) and a four-stage approach was used to undertake the SVP and engage with the advisory groups. The final product from the SVP is the Strategic Direction paper which will be presented March/April 2020 PGB Meeting.

67. The Strategic Visioning Expert Group comprised 12 members. Professors Louise Archer and Jonathan Osbourne were appointed as co-chairs of the group. The group's members are as follows:

Name	Organisation	Country
Professor Digna COUSO	Universitat Autònoma de Barcelona	Spain
Professor Sibel ERDURAN	University of Oxford	Multiple
Dr Jasper GREEN	University College London	UK
Sir John HOLMAN	University of York (UK)	UK
Professor Maria LEMOS	University of Michigan	Brazil
Bethanie MAPLES	Stanford University	NZ/USA
Professor Enrico NARDELLI	University of Roma | Informatics	Italy
Professor Graham ORPWOOD	York University (Canada)	Canada
Professor Saul PERLMUTTER	University of California, Berkeley	USA
Dr Bonnie SCHMIDT	Let's Talk Science	Canada
Professor Louise ARCHER	University College London	UK
Professor Jonathan OSBORNE	Stanford University	USA/UK

68. Two further members of the group (from India and from China) were unable to participate, one for personal reasons and one due to the Covid-19 travel limitations.

69. The Science Advisory Panel is a collection of international representatives of science organisations with views on the global future trajectories in the world of science and the requirements that these trajectories place on education in the future. It includes international representatives from science subject content and skills expertise across different disciplinary areas (for example, biology, chemistry, physics); industry, including Small and Medium-sized Employers (SMEs) and large multinationals across STEM industry areas; academia, professional societies, teachers/teacher organisations; policy-makers; government departments; and assessment bodies, grassroots organisations, STEM equity-focused organisations.

70. The SVP used a four-stage methodology, described below.

71. During Stage 1 (Engage), a qualitative survey was issued to the SAP that elicited approximately 400 responses. The executive summary from this survey is shown in Appendix 2 and the full report of the survey is available on request. The initial analysis of the survey provided five focus areas of discussion and exploration by the SVEG.

72. During Stage 2 (Synthesise), a three-day meeting was held. On day one, practitioners debated their views and directions in education. These views were captured by two of the SVEG and used in further discussions. On day two, 21 panellists presented against the five focus areas identified from the survey and responded to questions from the SVEG. On day three, the SVEG worked as a group to create the first draft of the Strategic Direction Paper.

73. During Stage 3 (Validate), a quantitative survey will be issued to the SAP, to gather views on aspects raised in the Strategic Direction Paper.

74. During Stage 4 (Publish), the Strategic Direction Paper will be presented to the PGB and discussed at the PGB meeting in March/April 2020. A final version of the Strategic Direction Paper will be published and passed to the SEG to undertake the framework update.

Appendix 2 - Qualitative Survey Issued to Science Advisory Panel - Executive Summary

Methodology

75. A wide-reaching survey was sent to the Science Advisory Panel (science professionals across a range of industries and countries). Respondents answered six broad open questions allowing rich and detailed feedback. In analysing the data, common themes have been identified and quantified using coding frames, typical of a qualitative survey analysis.

Key findings for each research objective

Research Objective 1. What should the core purpose of science education be? Is this changing and, if so, how?

76. Respondents described the core purpose of science education to involve providing "educational inputs" in order to derive "desired outcomes". The educational inputs required to achieve the desired outcomes are wide and varied, ranging from teaching fundamental scientific knowledge/content, to developing higher order cognitive skills, such as critical thinking, communication skills, or creativity. The desired outcomes were also varied and could be broadly described as a means to achieving 'social justice' whereby all individuals are able to become active citizens. Specific desired outcomes included:

- Personal outcomes, e.g. building an understanding of the world to enable the individual to fully participate in it
- Societal outcomes, e.g. providing skills to address societal challenges, including inequality
- Environmental outcomes, e.g. delivering an understanding of the science behind climate change so that scientists of tomorrow have the necessary requisite knowledge to mitigate this emergency.

77. Respondents reported that they believe the role of science education to be changing, specifically to involve greater focus on scientific skills and placing less emphasis on learning of knowledge and memorisation of facts.

Research Objective 2. To what extent do you feel that science education currently prepares young people for the world of work and to become scientifically literate, active citizens?

78. Although respondents found it somewhat difficult to generalise, respondents reported that, in many cases, current science education fails to fully prepare learners for the world of work and to become scientifically literate, active citizens. Four in 10 respondents indicated that preparation was negligible, while a further 3 in 10 indicated that science education prepares learners to a small extent.

79. The main perceived failing of current science education is that it places too much emphasis on learning content or memorising knowledge in order to pass standardised examinations, and too little emphasis on higher order cognitive skills and broader scientific literacy, which is considered essential in order to successfully engage with the world.

80. Respondents did acknowledge that science education does deliver knowledge of core concepts which are the foundation of future learning, however these are often not built upon.

Research Objective 3. What aspects of science education are currently working well or are less successful in your view? What would you like to see more or less emphasis on?

81. As noted in the summary of answers to research objective 2, the main perceived failing of science education is the prioritisation of knowledge over skills. With that in mind, there are a number of changes that respondents would like to see made to how science is taught:

- Changes to pedagogy to place more focus on higher order cognitive skills, particularly the application of knowledge in the form of experimentation, with clear links to the real world, and interweaving cross-curricula learning opportunities
- Respondents wanted to see greater focus on achieving social justice, brought about by widening participation in science, improved career prospects, facilitated by better links between education institutions and industry, and to promote a more general love of science
- Changes to curriculum and teaching content, which is often felt to be too broad (meaning that breadth is prioritised over depth), too outdated, and generally too disconnected from many of the skills that are necessary to be successful in science, technology, engineering and mathematics (STEM)
- Some respondents also described wanting greater focus on areas of innovation and change, whether these be environmental changes (the climate emergency being mentioned by a number of respondents), technological changes (e.g. growing importance of data) or societal issues (e.g. impact of globalisation).

Research Objective 4. Can you suggest any changes in science education that would help to recruit a more diverse workforce (in terms of gender, ethnicity and socio-economic background)?

82. Respondents suggested a number of possible solutions to improving the diversity of the STEM workforce, including:

- Providing positive role models for all minority groups, including improving visibility for minority science professionals, making sure to celebrate the success of scientists from underrepresented groups, and generally ensuring that the teacher population is balanced to ensure a mixture with regards to gender, ethnicity and socio-economic background
- Many respondents feel that moving from a knowledge/content focused teaching approach to a pedagogy involving greater science application and experimentation would also be beneficial in terms of widening participation in science as this is felt to more engaging, and overall a better pedagogy for teaching delivery to ensure scientific literacy
- Respondents suggested that the current teacher workforce should be supported and trained to help them understand how to better support individuals from minority backgrounds, whether that be specific training, or simply alleviating some of the day to day burdens that may prevent teachers from being able to focus on addressing this challenge
- Other suggestions included creating stronger links between schools and industry in order to raise awareness of science, technology and engineering career options,

introducing teaching content that is intended to appeal to a diverse student population, and creating targeted outreach programmes to provide more opportunities to participate in science outside of formal education.

Research Objective 5. What challenges might students face in their future beyond 2030 that science education should prepare them for, both in the workplace and society or the world at large? What new skills and competencies will they need to develop?

83. When projecting ahead to 2030, respondents predict a rapid pace of societal, technological, and environmental change, which makes accurate prediction of the specific skills needed to succeed very difficult, if not impossible. Instead, participants tended to talk about broad skill-sets that would enable learners to adapt to unforeseen challenges that they are likely to encounter in the world post 2030. These answers could be categorised broadly into three groups:

- Development of higher order cognitive skills facilitating individual adaptability. This was felt to be absolutely essential in order to thrive in an unpredictable future where change is rapid. Such skills included mental adaptability, critical thinking skills, communication skills, problem-solving skills, and creativity, amongst other skills.

- Focusing on social justice, broadening participation in science and tackling inequality. Respondents also discussed how science has a key role to play in ensuring social justice. In a world that is increasingly complex and where science is everywhere, individuals who lack scientific literacy will be unable to participate as fully as those who have a good understanding of the scientific approach.

- Preparing for innovation and change. Respondents were hesitant to be drawn into making specific predictions with regards to the changes and challenges that will face learners in 2030 and beyond, however some broad themes did emerge. Most widely cited was the challenge presented by the imminent climate emergency which is creating a pressing need for greater understanding of the environmental sciences. Technological changes, such as artificial intelligence, machine learning and automation are also considered to be highly likely to disrupt the workforce and wider life in general. Finally, there is a sense that advancements in biomedical science will be increasingly important.

Research Objective 6. What three changes would you recommend for future government education policy and/or expenditure in the sciences and STEM?

84. Respondents suggested four broad means by which the government can support science and STEM in general:

- Recruiting and retaining teachers, and removing barriers to high quality teaching. The most widely mentioned government intervention was to ensure high quality teaching through a mixture of plentiful ongoing opportunities for teachers to participate in continuing professional development, recruiting science specialists, removing bureaucracy (and in so doing shifting focus back to teaching), and generally ensuring that scientists have a voice when decisions are made with regards to how science should be taught in schools

- Adequately funding for science programmes and providing necessary teaching and learning equipment. Many respondents talked about the necessity of providing adequate funds for science education. Without this it was felt that it would not be possible to apply scientific knowledge and conduct experiments, which is seen as critical to developing scientific literacy

- Changes to curriculum and exam/assessments. Other respondents talked about a need to review the science curriculum, which is widely felt to be outdated, too broad, and prioritising knowledge over skills. Tying into this was a perceived need to review the current exam system, which is not felt to support effective teaching/learning of science as it is too knowledge focused, and does not test skills
- Implement strategies aimed at widening participation in science. A final recurring theme that stood out was a need for government to implement a concerted programme for widening participation in science. This is seen as critical for success in a fast-changing and complex world.

Appendix 3 - Informatics

85. Informatics, the science of digital systems, provides and develops the scientific knowledge allowing to build these systems, which exist independently of the computer. They automatically and mechanically process data and affect the physical world (for example: a system identifying one as a criminal or potential one, or deciding whether one is guilty or deserve some social benefit). These systems contain knowledge (expressed in the data and their processing rules), which, unlike the knowledge in books, is "actionable knowledge" that can be put to action without any awareness or understanding by the user of the meaning of either the data or the processing rules (Nardelli 2018). Even without this awareness, these systems are capable of replacing human beings in many knowledge-based jobs, without having their flexibility and learning capability. Some relevant example of knowledge areas of informatics:

- Representation and modeling of data
- Automata (computational model)
- Algorithms
- Programs/programming languages
- Computability
- Complexity
- Distributed/parallel computation and concurrency

86. Every young person should possess the fundamentals of such knowledge in order to be an active participant in the digital world. The SVEG has identified informatics, as a core knowledge area that supports preparing young people for an increasingly digital age, as well as enhancing their understanding of scientific processes.

87. This is in addition to the recent developments to the PISA 2021 Mathematics framework, which identified the need to incorporate computational thinking into the assessment, but restricted its focus to a mathematical context. As such, within the PISA 2021 Mathematics framework, computational thinking competencies include pattern recognition, designing and using abstraction, pattern decomposition, determining which (if any) computing tools could be employed in analysing or solving a problem, and defining algorithms as part of a detailed solution. Computational thinking in mathematics complements the proposal by the SVEG to incorporate Informatics into the Science Framework. Across the domains, it is necessary to address the data-literacy knowledge and competencies most relevant for the domain to ensure young people are prepared for data-dominated futures.

88. There are a number of competencies related to informatics that could be considered for inclusion within the PISA 2024 Science framework:

- understanding that for a machine it is necessary express algorithms in an unambiguous way;
- recognizing that algorithms are able to solve problems;
- being able to discuss the correctness of an algorithm;
- understanding the nature of the problems that are worthy of an algorithmic solution;
- being able to evaluate the efficiency and correctness of simple algorithms;
- defining, implementing and validating programs and systems that model or simulate simple physical systems or familiar processes that occur in the real world or are studied in other disciplines;
- understanding when programming can provide a convenient way of tackling a problem;
- recognizing that the way data are represented and organized affects the effectiveness and the efficiency of computation;

- knowing the main (physical and functional) architectural principles of a computer-based system;
- recognizes the fundamental mechanisms by which computer-based systems communicate and provide services on the networks.