Part 1
Educational Transitions in Context

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Cognitive Context

Bridging the Twenty-first Century Gap in Education – History, Causation, and Solutions

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This article discusses the gaps in the cognitive demands of education as higher levels of education became socially and culturally necessary. These gaps are related to major transitions between education levels, such as the transition from preschool to primary school, from primary to secondary, or from secondary to tertiary education. Gaps reflect deviations between the concepts and skills prescribed for learning by a specific population and the readiness of this population to cope with the demands of the task within the time frame prescribed. The history and the cognitive developmental profile of the gaps is outlined. This article focuses on the gap between secondary and tertiary education. It is explained that a major reason for the gap is the vast expansion in the population of youth attending university studies. We outline a programme for bridging this gap, which extends from primary to university education. We emphasize changes in principle-based and critical thought that are needed by many students if they are be able to grasp science as intended by universities.

A gap requires two distant sides to exist. In education, students and instruction are the two sides of the gap. A gap between them implies that students cannot cope with the new learning demands when moving from one level of education to the next. These gaps are related to major transitions between education levels, such as the transition from preschool to primary school, from primary to secondary, or from secondary to tertiary education. Gaps reflect deviations between the concepts and skills prescribed for learning by a specific population (e.g. reading and writing in early primary school, algebra in early secondary school, scientific theories at college) and the readiness of this population to cope with the demands of the task within the time frame prescribed. For instance, at transition from preschool to primary school, ideally all children must be ready to acquire the skills needed to learn to read and write at first grade; at transition from primary to secondary school, ideally all children must be ready to learn basic algebra or science concepts. This requires that children are prepared by the previous level of education, preschool in the first and primary school in the second example above, to cope with the learning tasks of the new level. For instance, in reading, to focus on visual patterns, connect them to phonological patterns, and integrate them into words; in algebra, to generalize numbers into abstract dimensions and operate on their logical relations. A gap would exist between two levels, if the new learning tasks are impossible for a large number of children. Obviously, gaps may appear in any school year for individual students for various reasons, such as specific delays in their intellectual development relative to a school subject, teachers' failures to meet specific needs of individual students, etc. However, these gaps are treated as individual learning difficulties rather than gaps between educational levels. This paper focuses on gaps between educational levels rather than gaps in individual learning and development.

The meeting of Academia Europaea (the European Academy of Sciences and Humanities) on bridging the gap between secondary and tertiary education reflects a problem of concern in our universities: many students admitted to universities are not ready to grasp science as required. This gap has several serious implications. For instance, it may compromise the quality of education and professional skills provided by universities. Alternatively, it may cause students to change programmes of study or to drop out altogether, disturbing universities, personal or family lives, or various aspects of the economy or production (SUnStAR 2019). I shall argue here that this problem is not unique for our time. It is a signal of a major change in the knowledge and cognitive skills required by society at its current stage of development. It happened in the past when similar changes occurred. Below, I shall first place the problem in an epistemological and historical perspective. Then I shall analyse the problem from the perspective of cognitive and developmental science and propose ideas for its solution. Table 1 summarizes the three major educational gaps discussed in the paper, the solutions implemented so far, the residuals problems remaining after bridging the three gaps, and the skills still lacking from explicit educational goals and programmes.

Cultures of Knowledge and Science

Three cultures of knowledge thrive in the modern university: natural sciences, social sciences, and humanities (Kagan 2009). There are commonalities and differences between these cultures. They are all supposed to be driven by truth in their attempt to describe and understand the world and motivate improvement of human life. They all involve a long history of scholarship which generates complex and demanding systems of knowledge and related professional activity. Mastering a discipline in each of them requires learning a body of knowledge which is often highly abstract and very distant from observable reality. One might mention here relativity in physics, DNA in biology, general intelligence in psychology, deep structure in linguistics,

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Table 1. Summary of education gaps and solutions implemented.

Educational Gaps	Learning tasks	Solutions implemented (or needed)	Residual problems	Skills not explicitly taught
From no to primary education	Reading, writing, arithmetic, basic concepts and skills of learning and functioning in the society, general science concepts related to actual life and experience, basic problem-solving skills.	Compulsory preschool-education, learning science-based programmes for teaching reading, writing, arithmetic and other concepts and basic study habits.	Specific learning difficulties, e.g. dyslexia, dyscalculia, behavioural problems at school.	Teaching of executive control processes, such as attention control and representational awareness.
From primary to secondary education	Reading and understanding of complex texts, self-guided learning and knowledge acquisition, grasp of abstract concepts from different disciplines, problem-solving of new/unfamiliar problems.	Compulsory junior secondary education, new learning science-based curricula.	Literacy and numeracy difficulties, failure to grasp basic science concepts, low adaptability in unfamiliar environments.	Systematic rule-based thought and its main underlying reasoning tools. Grasp of principle-based reasoning. Awareness of inference as a problem-solving tool.
From secondary to tertiary education	Grasp of scientific theories, models, and methods, mastering of high-level professional skills required for professional problem-solving associated with one's discipline.	University-oriented curricula in various subjects.	Failure to understand science as a systematic self-correcting approach to understanding and changing the world.	Differences between cultures of knowledge (i.e. natural, social science and humanities) in concepts and methods. Critical/epistemic reasoning. Logical awareness, accurate self-evaluation in different domains.

Keynesian theory in economics, literary theory in literature, etc. It also requires learning methods and codes of operation ruling how theories may be evaluated, combined, improved or rejected. In their professional applications, they involve knowledge and rules underlying problem-solving in related professions, such as the relations between the natural sciences and engineering, biology and clinical practice in medicine, theories of learning and education, etc.

These three cultures differ drastically, despite their similarities. The natural and social sciences are taxonomic, causal, explanatory, and predictive. Their primary aim is to model causal relations between variables and allow predictions for some of them based on others and their control, if needed. In the natural and social sciences, truth is approached by systematic observation, controlled experiment, and evaluation of findings by formal methods (mathematical or statistical modelling) allowing one to test if predictions and evidence fit. Theories are chosen based on their predictive accuracy, cohesion, and scope. However, modelling in the social sciences is more complex and less solid than in the natural sciences because the source of all units of interest, the individual, often unpredictably and uncontrollably, introduces variables not accounted for by the model being evaluated. Thus, the social sciences involve an extra layer of uncertainty that is not involved in natural science.

The humanities also try to understand and account for individual and social behaviour and its products such as literature, historical events, and ideas. However, this does not come through the scientific methods of truth control of the natural and the social sciences. In addition to personal observation, the primary source of information here lies in written texts or historical evidence about the phenomenon or the condition of interest. Their primary aim is rather to relate and evaluate approaches, interpretations, or sources of evidence rather than the behaviours or actions themselves. The very products of human activity, such as literary products, traditions, and ways of life are the primary object of analysis. Thus, interpretations are often perspective-based rather than based on 'objective' methods of testing truth. In the natural and social sciences, the concern about bias is central and, thus, methods for bias elimination are important in the process of discovery and modelling. In the humanities, bias may be part of the inquiry as such. Hence, the current discussions and theories about 'post-truth' or 'meta-truth', assuming that no objective truth is possible (Higgins 2016).

Obviously, there may be large variations within each of the three cultures. For instance, mathematics is very special because exploring and specifying formal relations between constructs dominate over empirically based relations. Legal science, placed between the social sciences and the humanities, prioritizes institutionalization of moral or social principles governing human behaviour, based on political decisions as prescribed by political institutions and processes. As a result, the study of law is a formal rational system guided by cohesion of principles, laws, and rules and their implications for the individual, social groups, and institutions.

Any aspect of reality may be understood at different levels. For instance, the preschooler understands that rain is water falling from the sky (realistic representational thought); the primary school child understands that it is recycled evaporated water going from sea to clouds and back (rule-based relational thought); the secondary school student may understand that it is a dimension specifically related to other dimensions, such as atmosphere temperature and pressure; the meteorologist (and the university student) understands that it is a parameter in a model allowing predictions of possible precipitation based on the values carried by other related parameters in the model. Also, any aspect of reality may be the object of any science: rain may be the object of meteorology, as above; the social sciences, when we explore how weather interacts with social behaviour and fashion; the humanities, when we explore tales, myths and traditions about rain across the globe and possibly related literature, etc.

Therefore, understanding across the three cultures of knowledge, the natural sciences, the social sciences, and the humanities, may be equally demanding. Concepts, constructs, models, and theories are extensively remote from first-hand observable reality. Regardless of the specific paradigm, elements of reality are reduced in generalized or idealized constructs multiply related in complex hierarchies, relations are often variably quantified, expressed in domain-specific language or symbol systems which must be mastered ad hoc. Further, models must be understood as such in each paradigm and approached as temporary: they are tools of interpretation for as long as no better model is available; however, they are always subject to improvement in case of a better interpretation. Therefore, a critical stance is part of understanding and improving knowledge; reasoning of different kinds is a tool in the service of both. Admittedly, the ultimate level of abstraction and complexity may differ across paradigms, depending upon tradition, level, and language of description, and methods of truth and bias control. For instance, models in high energy physics or astronomy are far more remote from reality and they are stated in a very idiosyncratic language as compared with models about literature, which express human experience and are stated in natural language. These differences may relate to differences between disciplines in their mental demands for understanding and operation, which in turn may differentiate between students in their possibilities of success in different programmes of study. We will discuss these questions below.

Educational Gaps in the History of Education

Any time there was an increase in the demand for a new level of education, many students entering this level were not spontaneously ready to cope with the cognitive and social demands involved. With the passing of time, education gradually acquired the experience to minimize the mismatch between educational and learning demands of the school and the cognitive and social ability of students, enabling the majority of them to cope. I outline the major milestones in the history of education in the last century to highlight my argument. The solution of the problems caused by these milestones may point to the solution of the problem discussed here.

Primary education has expanded drastically since the late nineteenth century and became compulsory in most European countries in the early twentieth century (Benavot and Riddle 1988). The second industrial revolution in the late nineteenth century resulted in drastic changes in the knowledge and skills required for work in the industry of the time. As a result, basic literacy and numeracy skills and knowledge offered by primary education were necessary for everyone to be integrated in the new work and social environment. By the beginning of the twentieth century, primary education was compulsory in most European countries and North America (Murtin and Viarengo 2011). Compulsory primary education caused the first educational gap at that time, because many children entering primary school faced serious difficulties in learning to read, write, and grasp the basics of arithmetic and other concepts beyond everyday experience. Intelligence testing was initiated by Binet and Simon in France to help identify students in need of special support to learn at school. Testing spread quickly in other countries, such as the United Kingdom and the USA, because the need for it was high (Anastasi and Urbina 1997).

This gap does not exist anymore. Two types of solution were implemented. First, research on the learning processes related to the basic skills of numeracy and literacy and related teaching methods enabled education to develop more efficient methods for the teaching of these skills (e.g. Dehaene 2010, 2011; Kuhn 1979). Second, institutionalization of pre-school education prepares young children to adapt socially and cognitively to the social and learning demands of primary school (Saracho 2015). Thus, transition to primary school is generally smooth for most children because education developed specific methods geared to the capabilities and weaknesses of children entering primary school, such as modern methods for teaching reading or arithmetic at first primary school grade. There may be difficulties for some children in several school subjects, such as difficulties in learning to read or do arithmetic, but these are treated as special learning difficulties that may be dealt with by special education (Demetriou submitted).

The next gap came with the third industrial revolution in the mid-twentieth century and the fast social, economic, and technological changes following the Second World War. These changes raised the standards of knowledge and skills needed relative to those provided by primary school. They include the ability to read and understand complex texts in different areas, think abstractly to deal with changing and varying demands at work, and function across different social conditions of the modern city. Initially, these changes resulted in a drastic expansion of the demand for secondary education in the 1950s and the 1960s. At that time, it was soon realized that many students entering secondary education could not cope with the new demands. The gap here was related to the ability for abstraction of underlying relations or themes beyond the apparent to give meaning to unpredictable changes at work or in the social environment, grasp the role of symbols standing for abstract ideas and operate on them as in algebra, and grasp non-observable ideas, such as electricity or radio frequencies from physics, which became part of everyday life. These needs caused serious difficulties to many students moving from primary to secondary education.

The need to bridge this gap coincided in time with the cognitive revolution of the 1960s and the emergence of several theories related to education, such as Piaget's (1970), Vygotsky's (1986), and Bruner's (1973) theories. From a twenty-first century perspective, these theories may have proven inadequate to guide the development of specific learning environments tailored to the needs of different school subjects at different school grades. However, at that time, these theories were very instrumental in raising awareness about the cognitive and learning demands of several important goals of secondary education: dealing with possibilities rather than observed facts; grasping underlying relations rather than noting obvious properties and characteristics; using arbitrary symbol systems standing for abstract entities rather than realistic representations standing for personal experiences. These theories, at that time, motivated extensive research in cognitive development and learning of school-related concepts which, in turn, resulted in extensive improvements in the organization of primary and secondary school curricula (Kuhn 1979; Chapman 2001). Additionally, junior secondary education became compulsory in most countries. Nowadays, compulsory education is nine years in most countries of the world (six years of primary education and three years of secondary education) (Murtin and Viarengo 2011).

Technically speaking, the primary–secondary education gap does not exist anymore. Bridging this and the earlier gap is obviously related to the fact that general intelligence increased in the general population by about 25 IQ points over the twentieth century, as discovered by Flynn (2009). According to the results of the Program of International Student Assessment (PISA 2012), only a minority of the students at the end of their nine-year compulsory education operate at the two top levels of reasoning and problem solving addressed by the PISA tests in reading, mathematics and science. Specifically, a considerable number of ninth-grade students graduating from compulsory education in the OECD countries (about 20%) operate at or below level 2 in all three domains: in reading, students can identify the main idea of a text; in mathematics, they can connect similar pieces of information, extrapolate by inference, and apply basic algorithms to solve simple problems; in science, they can interpret simple observations or simple manipulations, but they cannot design controlled experiments manipulating extraneous variables. The majority of students, i.e. about 60–70% operate at levels 3 or 4: they may abstract a relation or idea running through several seemingly different contexts; they can grasp the meaning of abstract symbols and connect them to different realities or contexts as in algebra, and they can understand that things may be more complex than they look. These figures suggest that the transition from primary to secondary education works rather well.

The third gap, which appeared in the last 20 years, lies between secondary and tertiary education and is related to the so-called fourth industrial revolution. This revolution resulted in the drastic expansion and use of scientific knowledge in practically all aspects of everyday life (e.g. programming needs of home appliances and cars, acquiring or selling products through the internet, financial possibilities related to banking and the stock exchange, which require complex mathematics); unprecedented connectivity (e.g. internet, mobile phones, social media, and travelling); easy access to knowledge (e.g. Google). Access to problem solving through machine learning may be imminent. These changes created new jobs requiring long and complicated forms of education that can only be provided at the tertiary level (e.g. jobs related to computer engineering and information technologies) and necessitated upgrading studies previously provided by vocational or professional schools into university studies (e.g. car mechanic, nurse, accountant, or even teacher training). Also, the globalization of production and the movement of people transform societies and economies worldwide. Moving production from the West to the East and Africa resulted into the expansion of secondary education in these parts of the world. At the same time, it transformed western economies into service economies where science-based jobs (e.g. lawyer, engineer, biologist, and researcher in all domains) are in much higher demand than in the past. As a result, the increasing demand for university studies resulted in the university boom of the late twentieth and early twenty-first centuries, sending about 50% of secondary school graduates in many western countries to university. The EU target for 2020 is 40%; in some countries, such as Lithuania and Cyprus, it is already close to 60% and nowhere in the EU is it lower than about 25%.

In response to this demand, university systems expanded drastically. New universities were created in most countries, new programmes of studies were added to the traditional ones, and many professional schools in many countries, such as the UK, Greece, and Cyprus, were upgraded into universities. However, only a minority of students operate at the two higher levels of the PISA studies (10–15% in all three subjects), which require principle-based thought or formal thought, in Piagetian terms. Only at these two levels can students abstract ideas from texts in different domains and build a differentiated representation including central themes and complementary and conflicting modules. In mathematics, only students at these levels can model complex problem situations using formal mathematical language, specify similarities and differences between different problem situations, and reflect on, evaluate, and communicate their work to others. In science, students must operate at these levels to grasp proper scientific ideas such as evolution, test hypotheses by controlled experimentation, and integrate findings and hypotheses into models (NCES 2014; van Damme 2019). In other words, only a few of the students (about 15%) operate at the level of abstraction and mental flexibility required to follow university education as defined by the university. Yet, about 50% of each cohort continue to university. Simple arithmetic suggests that many students would face difficulties in following university studies. Below, we will first exemplify the cognitive basis of the gap and then advance several proposals that might help bridge it.

The Cognitive Basis of Educational Gaps

The human mind is a complex hierarchical system involving general and specialized mental processes carrying out different tasks for understanding, learning, and problem solving. Specifically, there is a powerful general cognitive ability guiding action, decision making, and problem solving. It allows the following: focus on information and process according to goals; select goal-relevant information and inhibit irrelevant information or actions; rehearse and relate information by inference; self-monitor processing and reflect on concepts and experience to reconstruct them so that they better represent the environment and guide action; when concepts resist understanding and problems resist solution, repeat recursively the processes above, varying concepts and ideas until understanding is recognized as better; encode new concepts and reconstructions into symbols, making their future use more efficient (see Carroll 1993; Demetriou and Spanoudis 2018; Jensen 1998).

Second, the processes are constrained by the representational and procedural specificities of different domains. For instance, social, quantitative and spatial information involve different mental objects and relations and they are prone to different types of representations, such as language in the social domain, mathematical symbolism in the quantitative domain, and mental images in the spatial domain. To function efficiently, general mental processes need to have facility with the representational and relational units defining each domain, such as words, grammar, and syntax in the verbal domain or numbers, arithmetic operations and algebraic relations in the quantitative domain, and visual images and mental rotation in the spatial domain (see Demetriou and Spanoudis 2018; Demetriou *et al.* 2018a, 2018b). Variations in the facility to use different representational systems may end up in large variations in performance in learning concepts in different domains. Individual differences in learning and school success in different school subjects such as language-based subjects in the humanities and symbol-based systems such as mathematics relate to differences in this facility. Academic tilt at the university may derive from these differences (Coyle 2019; Demetriou submitted).

General cognitive ability changes with development, drawing on a different mix of general processes. Overall, it gradually shifts from executive processes underlying attention and working memory control to inferential processes underlying inductive and deductive reasoning and self-awareness processes underlying self-monitoring, self-evaluation, and self-regulation. Specifically, at preschool, thought is marked by attentional control and awareness of the perceptual origins of knowledge. Children understand that they know what they perceive. In primary school, thought is marked by inductive reasoning and awareness of inferential processes. Children start to understand that they may fill in lags in information by inference. In secondary school, thought is marked by deductive reasoning, mathematical reasoning, awareness of logical constraints of reasoning, and accurate self-evaluation. For instance, they understand that starting assumptions constrain conclusions and they know their strong and weak points. The cognitive profile of different age phases constrains what can be learned and what problems can be solved (Demetriou and Spanoudis 2018; Demetriou *et al.* 2018b; Markis *et al.* 2017). Notably, the processes dominating in different developmental cycles corresponding to different school levels, such as preschool, primary, and secondary school, are the best predictors of school achievement at this school level. Therefore, training programmes directed to cognitive enhancement at different school levels must be adapted to these priorities (Demetriou and Spanoudis 2018).

Changes in developmental priorities are associated with different representational needs and possibilities. For instance, speaking at the age of two years; reading and writing at 6–7; grasping underlying relations and using mental rules at 8–10; mental production of possibilities and grasp of principles allowing their use and evaluation at 11–17; epistemic understanding, that is grasp of the origins of knowledge from different sources, such as theory, experiment or reasoning, and understanding of constraints and possibilities of different conceptual or knowledge systems based on their origins, at 18–25. Mastering a new representational medium opens new cognitive possibilities and it may also be the source of new challenges in approaching the world and learning. The major argument of this paper should be clear by now. Successive developmental profiles are associated with major historical gaps in the development and expansion of education over the twentieth century. Bridging the first two gaps at the collective level resulted into major economic and social changes observed in the twentieth century, such as the massive improvement in prosperity, quality of life and health in those parts of the world where this bridging was successful. Nowadays, these gaps may still be present at the individual level as experienced by children facing difficulties in reading and writing and in mathematics at the beginning of primary school or learning the abstract concepts and symbol systems required at secondary school. In a sense, these difficulties are the residuals of the gaps described above that still need to be dealt with by modern cognitive developmental and educational science. However, the third gap, associated with the grasp of principle-based and epistemic thought by the general population, is still present, hindering the grasp of learning scientific theories and methods at university.

It took humanity a few hundred thousand years to move from oral (when Homo sapiens appeared about 200,000 years ago) to written language (about 5400 BCE). Likewise, it took humanity a few thousand years to move from written language to the invention of abstract symbolic systems, such as those used in modern mathematics and science (at about the sixteenth century BCE or much later). Also, it took a few thousand years to move from the natural philosophy of the Greeks to modern experimental science. However, each of these changes is condensed in about four to five years in individual development as coached by school (e.g. about four to five years to move from speaking at 2 years to reading or writing at 6–7 years or four to five years to move from reading to using abstract symbolic languages as an object of thought in secondary school and another five to six years to having to assimilate scientific theories and methods at university. Obviously, evolution did not endow humans with specific brain networks dedicated to the learning of these feats. They are cultural products requiring enormous brain-rewiring by individuals. It is not an exaggeration to say that modern education in a very short period of time wires cultural products formed over millennia into individual brains that did not evolve for them.

Here we focus only on the development of inferential and knowing processes and their vicissitudes after the age of 7–8 years. In cognitive developmental terms, the lower levels of the PISA studies address rule-based thought and the higher levels address principle-based thought. It is important to specify these types of thought because they are intimately related to the theme of this paper. Rule-based thought enables one to access individual representations (e.g. a series of numbers in an arithmetic task, multiple observations in a causal task aiming to interpret a phenomenon, threads of a story), align them and identify relations between them (e.g. numbers double, a particular button causes the effect to be interpreted, all heroes of a story work for the same aim). Inductive and analogical inference are the major tools of rule-based thought (Gentner and Hoyos 2017). Rule-based thinkers can think deductively (e.g. if they know that 'if A then B' they infer that B will occur if A occurred and that if B *did not* occur A *did not occur either*). However, they may fall prey to logical fallacies, assuming, for instance that if B occurred, A will also occur, ignoring that B may be caused by other factors as well (Stanovich 2011). Rule-based thinkers are aware of inference and its role in generating new knowledge (Demetriou *et al.* 2018a). However, they are inaccurate in self-evaluations and self-representations, often resulting into optimistic characterizations of their own performance. Thus, special support is needed to help them regulate their learning behaviour so that their learning efforts are successful.

Principle-based thought allows a grasp of higher-order relations between rules, generation of alternative possibilities, and evaluation of the cohesion of concepts based on logic. Principle-based reasoning is a logical metaprocess that defines acceptable and non-acceptable inferences. Thus, deductive reasoning at this level allows resisting logical fallacies because each inference is considered from the point of view of alternative complementary inferences. For instance, they understand that 'if A then B' does not imply that 'when A does not occur B does not occur either' because B may occur for reasons other than A. Thus, truth control is integrated into a system of rational analysis and related actual empirical control that may rule out confounding variables. Principle-based thinkers are aware of the logical constraints underlying the relations between concepts and they systematically search for them to examine if they are present in an argument. Moreover, they are relatively accurate in their self-representations and self-evaluations. They have a differentiated self-concept where strengths and weaknesses are explicitly specified. Thus, they are able to monitor and evaluate their problem-solving endeavours and self-correct, if necessary. This allows them to make long-term choices, such as a course of studies or a profession.

Epistemic thought uses principle-based reasoning for the sake of grasping systematic fields of knowledge, specify similarities and differences between fields, and to locate gaps between concepts and observations, or inconsistencies between concepts, and tries to remove the latter by inventing new concepts accommodating and explaining gaps and inconsistencies. Epistemic thinking also enables one to choose between the form of solution appropriate for different types of problems (Kitchener 1983; Seppälä *et al.* 2020). Epistemic thinking and underlying principle-based reasoning allows systematic long-term work on competing or complementary systems of knowledge for the sake of integrating them into new knowledge systems or paradigms. One may invoke examples from the history of science here, such as Maxwell's equations for uniting electricity and magnetism, Newton's theory of gravity integrating force and movement, Einstein's theory of relativity for gravity, movement, space and time, Darwin's theory of evolution integrating palaeontology, zoology and heredity, or Freud's theory of behaviour and mental illness (see Kitchener 1983; Richards and Commons 1984; Seppälä *et al*. 2020; Kallio, 2020).

Prevalence of Cognitive Developmental Levels and Cognitive Ability

How are these patterns related to cognitive ability in the general population? Answering this question requires an integration of psychometrics with the developmental expression of intellectual attainment. This would enable transferring knowledge from developmental research to learning at school. In view of this aim, we transformed attainment on tests of reasoning development into an IQ-like score. According to our transformation, an average IQ of circa 100 points corresponds to rules-based thought attained at the age of 9–10 years. Provided that intelligence is normally distributed in the population, this implies that the majority of people function with rules-based thought. Intelligence higher than 120 IQ points corresponds to principle-based thought. According to many studies (Demetriou and Spanoudis 2018; Demetriou *et al*. 2018b; Shayer and Adey 2002), only the top 15% of 18-year-old students reach the top levels of principle-based thought in different domains, such as mathematics and scientific reasoning, even when systematically trained.

Understandably, the concentration of principle-based and epistemic thinkers is higher in universities than in the general population. In selective universities where students are admitted on the basis of nationwide competitive examinations, such as the SAT (USA), the GCSE (UK), or the Baccalauréat and Grandes Écoles (French examinations), about half of undergraduate students (48%) operate at principle-based thought level; about 10% in the humanities but 40% in the sciences operate at various levels of epistemic thought (see Demetriou 1990). These levels correspond to an IQ that is higher than 130.

These findings suggest that there may be multiple gaps between secondary and tertiary education. The first gap is related to the attainment of principle-based thinking. Principle-based thinking is the minimal requirement for grasping science concepts as required by the university. According to the evidence above, about 15% of each cohort functions at this level when they graduate from secondary school. Yet, depending upon which Western country we are looking at, about 50–60% of secondary school students go to university. Overall, then, about 35–45% of students admitted to a university would face difficulties coping with the demands of university education. Obviously, there are differences between universities, because highly selective universities do have a high concentration of students coming from this upper 15% of cognitive ability. This may be as high as 80% in Greek (Demetriou 1990), Finnish (Seppälä 2013), or American (Wai 2013) selective universities. The second gap is related to the attainment of epistemic thought, which is much rarer than principle-based thought. The majority of students operating with principle-based thought (about 60%) do not have the epistemic understanding required to grasp science as a model-theory building enterprise that is under continuous revision. These students may grasp abstract science concepts as such, but they do not embed them into the epistemological constraints and nuances of a discipline, let alone science at large. Seppälä (2013) found that there is a difference between classic universities (60–80%) and universities of applied science (50–60%). Supposedly, going through the years of undergraduate studies aims to build the epistemic mind required to grasp these aspects of science and operate with them. However, according to Seppälä (2013) this does not occur; she found that significant changes in the conceptions of scientific thinking do not necessarily take place during the years of university studies.

Expanding demand for university education leads many people to university although they are not ready to follow university studies as required. The challenge of our time is to bridge this gap by preparing these people to study as required. This may be the revolution of twenty-first century education in the way that bridging the primary and secondary education gaps was the basis of the revolution of twentieth-century education. Arguably, there is a Darwinian-like market force activated by this increased demand for university studies. The university system expanded by creating thousands of new universities catering for students who fail the standards of selective universities. The implications are grave for individuals and society: graduates miss the opportunity to expand their capabilities and knowledge and professional skills at the level expected from university studies; society suffers from problem-solving inferior to the needs and expectations of the complex world of our time (Arcidiacono *et al*. 2012; Wai 2013).

What Must be Done

Bridging the secondary–tertiary education gap must draw on how the two previous gaps were bridged. I recall that changes occurred on both sides of these gaps. To bridge the first gap, preschool education was introduced, and many adjustments were made in the primary school curriculum and teaching methods. To bridge the second gap, junior high school became compulsory and many changes occurred in curriculum and teaching methods on both sides of the gap. To bridge the secondary–tertiary education gap, deeper changes are required, probably starting at the end of primary school. These changes are outlined below.

We noted that many secondary school students who do not attain principle-based thought end up at a university. Therefore, education must be redesigned to ensure that all students going to university grasp principle-based thought at the minimum level required for university studies. This requires specific programmes aiming to support the transition from rule-based to principle-based thinking upon transition from primary to secondary school. At junior secondary school principle-based thought must be consolidated well as an approach to problem solving. Examples of relevant programmes are given below (see also Herrnstein *et al*. 1986; Klauer and Phye 2008). In senior high school, which is the doorstep to the university, principle-based thought must be systematically practised in all subjects, i.e. language and humanities, mathematics, and natural and social sciences. Probably, an extra pre-university preparatory year may be compulsory for students planning to follow university studies involving programmes designed to train epistemic thought. Some examples follow below.

1. Training Principle-based Thought

We conducted several studies aiming to transform rule-based thought into principle-based thought. One study focused on the core of the processes underlying this transition. Specifically, we (i) built awareness of the schemes of deductive reasoning allowing resistance to logical fallacies; (ii) trained students to become fluid in inventing relevant mental models for these schemes; (iii) familiarized students in using the schemes in different contexts; (iv) taught the logical structure of each scheme and the notion of logical contradiction; (v) taught how to adopt an analytical approach to logical arguments and differentiate between the stated and the possibly implied meaning of propositions; (vi) taught the notions of logical necessity and sufficiency. The study involved 8- and 11-year old children, allocated in a control and two training groups (Christoforides *et al*. 2016).

In terms of spontaneous developmental time, this training programme pulled children up by a developmental phase. That is, trained third graders handled problems at the level of principle-based reasoning *if aided by context*; sixth graders moved to this level regardless of content and context. Specifically, this intervention enabled them to master the logical fallacies of affirming the consequent (knowing that when A occurs B also occurs does not allow any inference about A when knowing that B occurred) and denying the antecedent (under this condition, knowing that A did not occur does not allow any inference about B). The key to this success was awareness of the inferential identity of each scheme and the principle of logical consistency. Logical awareness improved under conditions of intensive training and related to attention control and working memory. In short, third graders grasped the logical principles implicitly; sixth graders grasped the principles explicitly and performed accordingly. These findings showed that practically all children may grasp principle-based thinking at the end of primary school if properly trained.

In another study we examined if training inductive reasoning in mathematics and related awareness would improve performance in several aspects of mathematics and generalize to other aspects of intelligence (Papageorgiou *et al*. 2016). This study involved 10–11-year-old children. Children were instructed to identify the dimensions underlying various mathematical reasoning tasks involving number series varying on several patterns (e.g. double, triple, half, one quarter) and mathematical analogies, conceive of their similarities and differences, group them according to organizational rules, and build the problem-solving skills associated with each. Thus, they were required to explicitly encode the problem structures and processes and their associations. The emphasis was on formative concepts such as 'attributes', 'relations', 'similarity', 'dissimilarity or difference' and their instantiation in the various problem types. The change in the domain of mathematical reasoning was considerable soon after the end of the intervention and most of it was sustainable about six months later. The gains did transfer to other processes such as domain-free analogical reasoning, deductive reasoning, working memory and attention control. Obviously, training principle-based reasoning in a specific domain, such as mathematical thought, is also possible.

Shayer and Adey (2002) developed a complete intervention programme aiming to boost scientific reasoning in combinatorial thought, hypothesis testing by experimentation involving control of variables, and complex relational thought, such as proportionality and equilibrium of systems. At the beginning, students are introduced to the subject of investigation and learn the technical vocabulary needed. Then they work on examples varying on a series of levels of complexity, examining alternative hypotheses or ideas, resolving conflicts, and reflecting on findings related to hypotheses. They work on the task in small groups of three or four until they have gone as far as they can, eventually reporting to the whole class. The teacher's aim of this intervention may appear top-down, but it is bottom-up in terms of its collaborative learning practice. There was improvement because of the intervention in children of all levels. However, only children operating before training at advanced rule-based thought moved to any level of principle-based thought. Those already at an initial level of principle-based thought moved to consolidated principle-based thought. Also, trained adolescents significantly outperformed control schools at National exams in science, mathematics, and English.

2. *Epistemic Awareness and Critical Thinking*

In senior high school, the type of training attempted by the three studies outlined above must recur in different scientific contexts related to actual problems solved in different disciplines. The aim must be to enable students to understand several critical aspects of real science. For the natural and social sciences, students must understand that science is controlled abstraction, based on systematic experimentation. Thus, scientific concepts are abstract models, accounting for the world under specific ideal conditions, as reflected in the experiments. Scientific methods, such as controlled experimentation, aim to purify models from redundant or wrong assumptions and expand them to new domains. Thus, hypotheses derive from theories and must agree with the reality concerned. However, confounding with irrelevant variables may always be present and conceal reality. Thus, scientific theories are, in principle, revisable forever. Predictions are means for capturing and removing confounding variables because they express relations supposed to be true. If evidence does not come as predicted the model needs to be revised in the direction of the evidence. Scientific languages are conventions suitable to express scientific models. Thus, they are conventions free of bias that may exist in conventional language.

In addition, students must become aware of epistemological issues concerning the similarities and differences between disciplines (Seppälä *et al.* 2020). For instance,

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they must become aware that levels of certainty differ between cultures of knowledge such as the natural sciences and the humanities, based on their respective methods for truth control. It must also be understood that high levels of logical and conceptual cohesion do not necessarily imply truth vis-à-vis reality. A highly cohesive conceptual system may be empirically false. For instance, the Ptolemaic earth-centric system was cohesive and consistent with many real-life observations, but it was false because other facts were unknown or ignored. Also, in the humanities, a system may be internally consistent given the basic premises of a faith, such as Islamic law, but not fair from the point of view of another set of basic premises, such as moral principles and ensuing legal laws in Christianity or Buddhism. Finally, students must acquire an awareness of the major sources of confounding in different fields, such as the social sciences as contrasted to the natural sciences, or different disciplines, such as physics as contrasted to astronomy.

Critical thinking is the ability to embed cognitive functioning into real-life contexts and make decisions taking into account the information available together with an evaluation of possible outcomes and their possible value for both the present and the future. It is recognized that becoming critical is a long developmental process built on the cognitive and conceptual acquisitions of successive developmental phases. It is argued that no one can really be critical outside a specific conceptual system, because a critical approach is applied on established facts or ideas that need to be changed, improved, or abandoned. Being critical is also constrained by the current state of problems and the specific needs dominating at a specific time in a specific social group. However, there is research showing that increased general cognitive ability and the ability to decontextualize enhance flexibility in using prior knowledge appropriately in order to overcome personal biases and invent original solutions to problems (Sa *et al.* 1999).

Our research, then, suggests that critical thinking skills may be trained, together with cognitive and epistemic training as suggested above. This training would develop the following mental skills (see Demetriou and Spanoudis 2018):

(1) Focus on relevant information. Theories and models define what is relevant and what is not relevant for a theme or problem.
(2) Scan information, compare, and choose what appears relevant and what appears irrelevant according to the goal.
(3) Represent what is chosen as relevant and inductively and analogically associate it with knowledge already possessed.
(4) Specify what replicates and what goes beyond extant knowledge. Reason by deduction based on accepted assumptions to evaluate truth and validity of conclusions.
(5) Think of alternatives going beyond the problem and solutions under consideration, taking into account the needs a solution would satisfy relative to past solutions, or the new needs it may create.
(6) Look for evidence going against your beliefs; do not avoid it.
(7) Prefer solutions that are better, nicer, or broader than extant solutions. Estimate consistency with beliefs, extant theories, dominant views.

Obviously, training for principle-based thought and the critical stance to information, evidence, and interpretations is important for successful university studies. Additionally, however, principle-based critical thought is important for successfully operating in our complicated modern world. The demands of this world in the social and professional sphere exceed the possibilities provided by rule-based thought. Rule-based thought is not enough to overcome orchestrated misinformation and deception that abound in the modern media world (see Stanovich 2011).

Where the Gap Must be Bridged

Understandably, one might object that the intervention programmes addressed to bridging the gap between secondary and tertiary education may be demanding for secondary school so that it might be preferable for them rather to be implemented in the early years of university studies. Obviously, the terrain of these problems is not well charted, and more research is needed to guide decisions about how to prioritize actions that are more suitable for secondary education and actions that are more suitable for university. Perhaps, a combination might be better. On the one hand, a long-term programme for training principle-based thought starting from primary school and epistemic thought starting in late secondary school. This might culminate in a preparatory year at the transition from secondary to tertiary education for the students planning to go to university.

On the other hand, this would require that the university recognize its responsibility for preparing admitted students to grasp science at the level required. This would require a new stance from universities and related services. For instance, using diagnostic tools to identify students in need of the kind of support discussed here comparable to the way such tools are used, for instance, for pupils needing special support to learn reading and writing at the beginning of primary school. Based on the needs and individuals identified, the university would have to provide teaching programmes implementing the goals outlined above and staff trained to implement these programmes. I am aware that for many professors this approach may sound far-fetched and alien to the university. It must be recognized, however, that these needs are here to stay and will still increase, and we better receive the message rather than kill the messenger. Obviously, more research and thought are required before these issues are resolved at the level of policy making.

Conclusions

The twentieth century was the century of education. At the beginning of the twentieth century primary education expanded and became compulsory. In the middle of the century secondary education expanded and became compulsory. By the end of the century university education expanded drastically. It is not yet officially compulsory, but it is already almost so socially. This is unprecedented in the history of humanity. The social, economic, and technological implications will never be fully evaluated because the changes in these domains occurred together, probably in strong interactions. However, the implications for collective cognitive functioning are very great. The Flynn (2009) effect suggests that intelligence increased by about 25 IQ points over the twentieth century. This implies that education makes the human mind more effective and efficient 'in mental abilities related to planning, organization, working memory, integration of experience, spatial reasoning, unique problem-solving, and skills for goal-directed behaviors' (Baker *et al.* 2015, 144).

The expansion was not a smooth process. It came in steps with considerable gaps between them. This reflected the difference between the general cognitive readiness of the population for a new level of education and the cognitive demands of this level. In terms of the model used here to interpret the gaps and derive applications for their bridging, the increase in intelligence noted above came mainly from programmes directed to rule-based thought. That is, bridging the no education–primary education gap or the primary education–secondary education gap required investments in curricula development and methods boosting executive processes and relational thought, allowing pupils to grasp relations between representations. In fact, there is evidence that principle-based thought is not related to the Flynn effect because there are signs of decline of this type of thought over recent decades (Flynn and Shayer 2018). Therefore, the measures proposed here may end up, in the long run, triggering a next cycle of collective increase in secular intelligence, which would expand principle-based and epistemic thought in the world. Attention is drawn here to the last column of Table 1.

This column points to developmental priorities of general skills and processes of the mind built during each of the main levels of education. These are not explicitly trained in education. They are only indirectly trained through the various subjects and curricula associated with each level of education. The time may be ripe for special curricula for the teaching and training of these processes. In fact, the next educational revolution may be greatly facilitated by these curricula. We hope that this article will open the discussion needed for related decisions and policies.

Explicit training of these processes is needed for three important reasons. First, increasing intelligence does increase human capital, which ends up in increases in real capital and global prosperity (Rindermann 2018). Second, the coming of high-level artificial intelligence systems approaching human principle-based thought requires human beings that can operate at this level for them to be able to efficiently and beneficially use these systems. Third, the complexity of the world itself demands that citizens achieve a high-level moral stance that enables them to grasp this complexity and its implications. Obviously, it is up to the twenty-first-century state and the university to solve these problems.

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