TOWARDS EVOLVING ENGINEERING EDUCATION BASED ON SYMBIOTIC COGNITIVE DIGITAL TWINS

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Abstract –*In the long past, professional education lasted for a lifetime. Since then, the industrial revolutions have accelerated the pace of knowledge doubling from a lifetime to months, and shortened the half-life of pertinent knowledge. Those changes have altered the working environment of professionals who have to move between many jobs in their life. Are we capable of adjusting to that pace? How can we learn all that is needed in the old Prussian model of education based on one-program-fits-all? We should revamp the educational system at the core. The new system must be personalized to match the diversity of individual abilities and styles of learning. The new system must also be based not only on the body of knowledge (BoK), but body of experience (BoX) and body of humanity (BoH). The new personalized system of learning must be sufficiently agile and interactive so that it would become evolving in its symbiosis with humans. For that to happen, we must coexist with symbiotic autonomous cognitive systems, specifically involving digital twins. This paper addresses some aspects of this view.*

Keywords: Education systems; Prussian classroom; evolving educational system; engineering education; cognitive digital twins; symbiosis.

1. INTRODUCTION

The first industrial revolution has accelerated the need for many skilled individuals that could not be produced by the personalized Master-Student educational system of the past. What was needed was a well-organized one-fits-all educational system that could produce expected numbers of individuals with expected skills within a fixed period of time. The Prussian classroom education system of 1770 produced magnificent results. At that time, the acquired knowledge and skills lasted for at least a lifetime. The four industrial revolutions since then have accelerated the pace of knowledge doubling from a lifetime to months (knowledge tsunami), while reducing the half-time of pertinent knowledge, thus shrinking the resilience of jobs, so that young professionals are expected to have more than one job. How can they learn all of that in the old educational system?

The new educational and learning system must be personalized to match the diversity of individual abilities and

styles of learning, and must also be based not only on the **body of knowledge** (BoK), but also **body of experience** (BoX) and **body of memetic knowledge of humanity** (BoH). The system must be sufficiently agile and interactive so that it would become evolving in its symbiosis with individuals and society. For that to happen, we must coexist with symbiotic autonomous systems. In particular, we should learn how to interact with evolving digital twins that could help us in selecting what we must know in order to adapt more efficiently and to enhance our creativity in solving difficult problems, while protecting us from increasing enslavement and trading of us on the networks.

Several other reasons for the need to update our approach to education and learning have been described in [1]. One of them is the development of **digital twins** (DT), virtual reality, augmented reality, and mixed reality in industry and other sectors. Of particular interest are the developments of **industrial digital twins** (IDT). Definitions of such industrial digital twins and attempts to standardize them are being developed by many professional organizations, including the National Institute of Standards and Technology (NIST) [1A].

The hope is that the IDT would also develop into **cognitive digital twins** (CDT) and **symbiotic digital twins** (SDT) with sufficient capabilities to augment our physical and physiological limitations, and find proper ways to be helpful in our adaptation to the untenable challenge of doubling of knowledge over a rapidly decreasing time period. Another challenge is the need to educate individuals for more than one job due to automation, mechanization, and the unprecedented growth in deep learning (DL) [2] and artificial general intelligence (AGI), as described in the Symbiotic Autonomous Systems (SAS) White Papers I and II [3]. Some challenges in developing better engineering education in cognitive systems are described in [4], [5]. The CDT concept and its implementation are becoming feasible [6].

There is another reason for digital twins: the knowledge half-life. In his book *Future Shock* [7], Alvin Toffler stated that “the illiterate of the 21st century will not be those who cannot read and write, but those who cannot learn, unlearn, and relearn.” The knowledge and skills acquired in our schools and successive jobs diminishes in value, and requires continuous updating, not once but throughout our lives.

How long does it take for knowledge to become outdated and irrelevant, or even incorrect? The half-life of knowledge (i.e., the amount of time it takes for knowledge to lose half its value) is often used to indicate the devaluation of knowledge in various disciplines. As might be expected, the knowledge half-life in aggressive disciplines like science, engineering and technology is shrinking fast.

2. SYMBIOTIC DIGITAL TWINS

2.1 Is There a Digital Twin of Me Already?

In a way, each of us has already several fragments of our own digital twin. Social media like Instagram and Facebook, LinkedIn and Twitter are all collecting parts of our “self”. Governments and municipalities are also collectors of parts of our “self.” The health-care system “knows” much about our body and mind. Large physical department stores, as well as digital merchandise systems like Amazon “know” much about our purchasing needs and interests (electronic products, mechanical gadgets, books, music) so that they often suggest new and related products. Google has a deep insight into its users’ interests ranging from scientific, technical, conceptual, philosophical, artistic, political, social, to theological. Travel companies know our interests about the world and our disposable income. In addition, the companies where we have been working and where we work now have other fragments, representing our acquired skills and habits. Insurance companies know much about our health risks. The educational institutions that we have used are also collecting records of what we have learnt, how good we are at specific subjects, and can assess our intellectual potential. All of those fragments approximate of what and who we are. They are distributed elements of our **personal digital twins** (PDT).

At this stage, all those fragments are dispersed and **owned** by specific companies or organizations in order to bring financial or other gain to them. Some countries are developing rules to establish ownership of those fragments. For example, Italians have the right to access these data and information, and the companies physically storing the data have to grant them access. Having the right and actually being able to access them easily are quite different and will have to be synchronized. But by whom?

2.2. Naïve Digital Twin (NDT): Aggregation of Fragments

Since the number of collected observations in the form of structured and unstructured data has been expanding at an accelerating rate due to the ever-advancing connectivity and interconnected networks, together with increasing capabilities to extract relevant and useful information and knowledge about ourselves, more accurate representation of our “self” is now within reach. Consequently, one of the critical objectives

of this new development is to aggregate those fragments into a more comprehensive one in order to represent our “self” better.

2.3 A Symbiotic Digital Twin (SDT)

If we imagine a symbiotic relationship between a person and the corresponding naïve digital twin, the symbiotic counterpart could form a very good approximation of what we are, often through direct access to what we do jointly, and through the access to other digital twins of ourselves and even others.

In a formal way, our digital twin could come to represent both our current skills, knowledge, and wisdom. It should also have the ability to take into account the **fading away** of our **skills** (those that we lose when not practising), as well as our **knowledge** (when we either forget, or when our current knowledge becomes obsolete due to new developments). This information of our degrading skills/knowledge can be the starting point for a **proactive education program**.

Our symbiotic digital twins can also mirror our process of creating and researching new ideas and writing technical reports and articles about them, as well as presenting the papers at conferences, or attending a conference to listen to colleagues presenting their papers. This also applies to the process of reviewing papers. Since many publishers allow ongoing discussions on their published papers, our digital twin could monitor and share the most relevant observations with us. Educational institutions and organizations, including the Institute of Electrical and Electronics Engineers (IEEE) and the Association of Computing Machinery (ACM), could contribute to the mirroring of their professional members, as well as their graduate and undergraduate students into digital twins.

Such information would be critical in creating **customized and personalized education programs**. An example of such a program is the *personalized system of instruction* (PSI) by Fred S. Keller (1899-1996; 97) [8]. Since the manual administration of Keller’s PSI is very tedious, we have developed a *Computer-Aided PSI* (CAPSI) that has been running at the University of Manitoba, Canada, for many years [9].

In a **symbiotic autonomous system** (SAS), the skills, information, knowledge and wisdom should be shared among its component subsystems to enhance the overall performance of the system. Furthermore, the symbiotic digital twin could start increasing (or decreasing) interaction between its component parts. Notice that in dynamical complex systems, the whole is not necessarily the sum of its part. Through such nonlinear interactions, an emergent quality may appear that may not be found in any of its parts alone.

2.4 How Can a Symbiotic Digital Twin Help Me in Skill and Concept Learning?

If I live in a symbiotic relation with my appliances at home or at work, the knowledge of what specific selection/action/effect (a "program" for short) I would most likely to be interested in at a given time becomes part of the global knowledge of the symbiotic digital twin. However, the knowledge about what programs are available and would fit my interest may lie in an appliance. Notice that Amazon's Alexa, Apple's Siri, Microsoft's Cortana are all moving in this direction. There are now thousands of programs (such as streaming contents) to choose from and be of serious interest to me. However, there are just too many for anyone to be aware of at any given time. The same applies to the millions of YouTube clips, tweets, and other pieces of information that could become an integral part of my education process, but I will never know that they even exist.

The same scenario can be envisaged with studying magazines, white papers, reports, textbooks, monographs, and research papers. Another scenario emerges with all the courses and MOOCs (massive open online courses). Such courses are now available at Coursera (launched in 2012 by Stanford University with over 2,000 courses), EdX (launched in 2012 by Harvard University with over 1,200), Udemy (over 2,500), Udacity (200), MIT Open-CourseWare (2,200), XuetangX (founded in 2013 by Tsinghua University with over 500 courses), Lynda (3,300), Khan Academy (started in 2006 by Salman Khan, TED with 1,890 courses), The Great Courses (500), and over 700 universities offering MOOCs (e.g. [10] [11]). Designing of online courses is discussed in [12] and improved comprehension in [13].

A similar scenario emerges when doing research. Research focusing is very time consuming (e.g., finding and reading relevant research papers, technical magazines, technical reports, white papers, and technical books). These are all examples of the "where can I find it?" problem in education. A symbiotic digital twin could help in these situations.

2.5. What Prevents Us from Having the SAS in Education Today?

There are at least three missing links to create a symbiotic autonomous system (SAS) in education: (i) a reasonable cognitive digital twin itself, (ii) symbiotic interconnects, and (iii) rigorous modelling of SAS.

While the concept of a digital twin is not new [1A], the concept of a digital twin of a human is fairly new. While attempts are being made to develop machines and systems capable of acting in a manner that could be described as: adaptive, autonomous, intelligent, perceptual, cognitive, conscious, and symbiotic with humans and the environment, symbiotic digital twins are not here yet.

The second missing link is the connectivity between the different parts of the symbiotic system. When the Internet has been developed sufficiently, we thought, happily but mistakenly, that education could be improved on a dime by delivering many online courses (in different forms such as the massive open online courses, MOOCs) to many people at any time and any place. Of course, this helped, as millions of new individuals obtained access to education that was not available to them before. However, the interconnections were not symbiotic. We must develop a new class of symbiotic interconnects.

The third missing link is proper rigorous modelling of SAS based on brain-inspired and socially-inspired processes. This modelling also implies quintessential changes in signal processing and in the simulation of the processes. In the past, the majority of signal processing was done on a single scale (mono-scale). Later, more advanced models of reality included multi-scale signal processing. Cognitive system and SAS require not only more elaborate multi-scale, but also poly-scale modelling and signal processing. Some of the definitions will be provided in the next subsection, and summaries of the modelling techniques may be described in SAS White Paper III.

These three missing links are being addressed by increasing number of individual innovators, as well as by many specific initiatives supported by various scientific, engineering and technical organizations (e.g., IEEE or ACM).

3. LEARNING ECOSYSTEMS: SOME DEFINITIONS

3.1 Models of Learning

Education and learning have been existential to humanity, and have been evolving throughout the millennia. Recently, educational systems have been changing more rapidly as a result of sociocultural, political, economic, demographic, and technological changes [14]. New technologies (such as social media, serious games, adaptive software, software-defined communications systems) and emerging practices (openness, user modeling), have facilitated opportunities to transform education, learning, and particularly teaching. With the advent of the Internet, the brick-and-mortar education has been expanded to network-based education through distance education and training, as well as massive online courses (MOOC). Social media include: Facebook, Twitter, Flickr, Digg, YouTube, Upcoming, LastFM, Techorati, MyBlogLog, and SlideSharing.

What is learning? It is the acquisition of knowledge, or professional and other skills, through either self-study, or by being taught by parents, friends, teachers and/or tutors, or intelligent systems, or workplace, or organizations, all with different degrees of experience, starting from childhood,

through adolescence, to professional life and seasoned years. Learning occurs in a systematic way (schools, routine reading of scientific, technical and other news digests, discussions with family, colleagues and friends) and through the experiences and events that occur in life less predictably. This experiential learning is also fundamental in acquiring knowledge that is important in decision making. Learning alters the functioning of the brain [15].

What is education? We have just defined learning as the process of acquisition of knowledge in a discipline, hard and soft skills, critical thinking, creative thinking, values, beliefs, and habits. Education is then the process of facilitating learning by teaching, training, discussion, interactive experiential experiments, and directed research.

We learn best when acting on what we have learned, thinking about it, and actually participating in the real world. Effective and impactful learning requires that we immerse ourselves in the process completely: with our will, senses, feelings, intuition, beliefs, and values. It often starts from our own enquiry. This is a very important point to make: the impact of education on us is determined by our **engagement**; technology by itself can help, but is not a replacement for the engagement. For the symbiosis to have the multiplying effect, we must engage the technology too.

In the past, learning was modeled as a linear process in which progression through various educational events produced an additive effect. Today, researchers and educators model learning as well as growth and development as a nonlinear dynamical system. Our proposed educational system is intended to assist in our **engaged life-long learning** (ELLL) with the assistance of symbiotic digital twins.

A **learning ecology** includes (i) learning concepts, (ii) learning dimensions, (iii) filters, and (iv) conduits. Learning is a process that involves a number of foundational concepts, such as signals and noise in the real and/or virtual environment, observables and data, information, knowledge, meaning, understanding, wisdom, and vision. We learn because: we need to know, we want to do something, want to be somebody, want to create, transform, change (learning dimensions). Educational filters affecting our outcomes include values, perspectives and beliefs. Educational conduits include selected language, media, and technologies engaged in the process.

The educational process can be either formal or informal, it can be done through self-study or through communities, with the help of direct performance support or monitoring and mentoring, all gaining experience through simulation, emulation, experiential learning, internship, co-op, or apprenticeship.

3.2 Current Models of Learning

Marcy Driscoll [16] provided a classification of epistemologies including (i) **Behaviorism** (objectivism) in which reality is external to the mind and knowledge and perception are acquired experientially, (ii) **Cognitivism** (pragmatism) in which knowledge is a negotiation between reflection and experience, inquiry and action, and (iii) **Constructivism** (interpretivism) in which knowledge is an internal construction and is informed through socialization and cultural cues. De Corte [17] provided an overview of historical developments in the understanding of learning. There are many other learning theories and practices (e.g., [18]), including experiential learning, project-based learning, situated (context) learning, competency-based learning, problem-based learning, gamification, blended learning, flipped (inverted) classroom, cognitive apprenticeship, adaptive learning, team-based learning, individualized learning, personalized learning.

Since human behaviour cannot be fully understood by the reductionist behaviourist approach (decomposing the system into linear parts and then reconstituting it), the idea of Gestalt psychology has become more attractive in which the organized configuration of components in the whole system is considered. This approach to learning requires data-processing, as well as information-processing and knowledge-processing techniques.

Cognitivism and connectivism appear to be relevant to our proposed cognitive digital twins in a symbiotic network of machines, individuals and society to develop a digital-twin-based learning. However, there are several levels of fundamental challenges: we must learn how to (i) acquire new classes of data describing the learning processes and their dynamical interactions; (ii) create representative personalized knowledge and learning processes; (iii) create distributed knowledge and learning processes; and (iv) develop measurable mechanisms to protect the individual and the corresponding digital twin against potential harm.

Our longer-term objective is to develop a theory of the symbiotic digital-twin system. The theory must not only verify and explain the associated behaviour and phenomena through measurable observables, but should predict the future behaviour of the system within its horizon of predictability.

3.3 A Summary of the ODIKWaV Model of Situate Learning

Figure 1 illustrates a common progression of situated-learning stages from (O) observations of the environment leading to (D) data extracted from the observations to (I) information, (K) knowledge and action, (W) wisdom, and finally to (V) vision. This is often called the data-information-knowledge-wisdom (DIKW) pyramid model.

We have extended that model to include directed and purposeful observations to reduce the unwanted data. To know what constitutes **relevance** in data, knowledge and actions (experience) are needed. Responding to the environment only is not sufficient in the extended model, as for the observations to be relevant, a vision is also required, as described in [19].

The traditional knowledge pyramid (Fig. 1) includes wisdom in the expected outcome of the educational process, and is intertwined with the digital twin as an inverted pyramid. This is to emphasize the **complementary symbiotic relation** between an individual and the SDT system. Such an intertwined SDT and a person could be called a **symbion**. The diagram is also intended to imply that the symbions could penetrate the environment even deeper than the human alone. The system could participate in the data mining and processing to extract information more relevant to the individual and to the environment. It could possibly see more patterns in the information and extract more significant knowledge that could be used in the decision-making process. This layer is now the widest because the digital twin could also be connected symbiotically to all the relevant other symbiotic digital twins for consultation.

Fig. 1 The knowledge pyramid combined with digital twins form a new construct of a **symbion**.

3.4 Closing the Loop Through the BoX and BoH

We have also discussed how the engagement of symbiotic digital twins (SDT) could assist in the closing of our open-loop educational system when all the experienced individuals would be engaged in teaching the next generation of students by providing their experience, many of the soft skills required,

and above all the passion and motivation for critical thinking, problem solving, and creativity. This is the process of morphing a student into a committed professional where the **body of experience** (BoX) could be shared in the educational system [20].

There is another consequence of engaging digital twins in the process: in addition to passing the BoX to the students, they would learn about the optimal ways of passing the BoX to an individual, thus increasing the personalization of knowledge. An even more important consequence of the proposed approach is that the digital twins would learn the new acquired experience of the individual throughout their life, thus updating and enhancing the BoX itself. Under this arrangement, the BoK and BoX could be maintained and **retained** by the digital twins. Under the new DT-based environment to maintain and deliver the personalized BoK and BoX to each student, the role of the teacher and professor could then be elevated to a mentor to the student.

Throughout our history, humanity has developed memetic knowledge, ethics and cultures (BoH) that guided us through many difficulties in the past. Sharing this third element through cognitive digital twins could become very helpful in addressing and solving existential problems on this planet.

4. TOWARDS EVOLVING SYMBIOTIC EDUCATION

4.1 Summary of Reasons for Our Symbiotic Evolution

As we have discussed already, the knowledge tsunami and automation have added much pressure to change the current classroom/workshop model in vocational training. More students and workers learn “just-in-time”, and often just enough to solve a problem or get a job completed. Teachers and trainers can no longer be the main sources of knowledge about the world of work, but need new forms of technology to help find and manage the increasing amount of information. No single person, no matter how brilliant, can handle the required knowledge, even in one field of study.

Consequently, the roles of teachers, trainers and consultants have been changing from mostly presenters of information and knowledge to guides, mentors, curators of knowledge, critical thinkers, and problem solvers. They have to use digital learning skills and literacies.

Throughout this section, we have been making the case that the next generation of education would benefit much from the development of symbiotic digital twins capable of being **in relation** with human beings in a symbiotic system. This intimate knowledge of the personal needs and abilities could allow the digital twins to deliver not only the revised BoK, but also the enhanced BoX and BoH in a personalized way that has a chance to compete with the best model of the Oxford Master-Learner of the past.

4.2 Model of a Naïve Digital Twin

A model of the naïve digital twin that could be used in the symbiotic education could be segmented into three parts: (A) content creation, (B) operations and management, and (C) needs and delivery. Each part could also be subdivided into several groups of activities. For example, Part A has three distinct important content creators: (1) organizations, (2) groups, and (3) individual, as described in [17].

4.3 Expected Outcomes from Symbions

There is another possible outcome of using digital twins. Business intelligence gathering in cyberspace from individuals, companies, organizations, governments, countries and economic systems is already practiced today. Unchecked and unethical practices may, however, lead to a collapse of the system itself, as individuals may select to see the profitable part of the system only. We see an opportunity for the digital twins to help in resolving this age-old problem. Digital twins may actually enforce the ethical use of the system by operating ethically.

4.4 Possible Outcomes from Symbions: Deeper Insight and Purpose

Learning through the symbiotic relation between an individual and a symbiotic digital twin is potentially much more beneficial to the individual than alternative learning methods. The symbiotic pair (the individual and the digital twin), called here a **symbion** (Fig. 1a), can be connected with other symbions through the fundamental construct of a digital twin. The individual symbions can enter into symbiotic relations with other symbions, thus forming teams, communities, and societies, as shown in Fig. 2b.

The advantage of this modelling is the ability to study the dynamic behaviour of such teams and societies, using multiscale and polyscale techniques capable of identifying long-range dependencies that are important in predictive control in cognitive systems.

5. CLOSING REMARKS ON SYMBIOTIC EDUCATION

Symbiotic education has the promise of great impact on how we study, learn, acquire skills, interact with people and machines, discover new things, learn how to operate new things, and how to see reality much deeper. Symbiotic education can open up a new landscape for exciting new concepts and research projects. This professional symbiotic education could be very useful in expanding the impact of engineering education.

Symbions may also be important in this knowledge revolution era not only in helping us to be more creative in solving existential problems, but also in making us safer.

Fig. 2 The impact of symbions: New societies and new knowledge. (a) A single symbion. (b) A small self-organized self-affine team.

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