Digital Tools and Solutions for Inquiry-Based STEM Learning

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Chapter 6
Inquiry-Based Science Education and the Digital Research Triad

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ABSTRACT

The chapter deals with a new research field that has arisen at the intersection of scientific experiment and emerging digital technologies. The classical triad of experimental research 'subject-instrument-object' and its implementation in science education are in the focus of the chapter. The triad is studied in its evolution to a so-called digital triad corresponding to the experimental science of digital society. In the digital triad, each of the three components are transformed. The knowing subject - researcher is transformed to the digital scholar; the experimental instrument is transformed on the base of emerging cloud and mobile technologies; the research object comprising hybrid natural-artificial components emerges. The digital transformations of the experimental research triad and educational practices based on the digital triad are manifested in a number of pioneer inquiry-based projects analyzed in the chapter.

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INTRODUCTION

Global society has transitioned into the Digital Era; this shift represents a revolution in human history – the so-called digital revolution (Dewandre, 2011; Ess, 2015; Floridi, 2014; Turner, 2006; Yuan, 2013). This revolution relates to fundamental principles of humanity. It has changed peoples' understanding of their place in the world, as people no longer merely consider humanity a part of the nature, but also a part of the artificial world that humans have created. The digital revolution also changed peoples' perception of society. Digital society is a hyper-connected one, in which people may have hundreds of acquaintances living in distant parts of the planet, with whom they exchange information. Presently, moreover, people have unlimited and ubiquitous access to desirable information, which, in turn, becomes personalized and context-cognizant. Indeed, our world has become one of information abundance. This state, in contrast to the previous state of information scarcity, comprises one important characteristic of digital society (Ganascia, 2015).

Indeed, the digital era has led humanity to take on a new perspective on its surrounding environment. People are gaining an awareness of the fact that we live not only in a 'real' environment, but also in a virtual space. Such a 'twofold reality' has led to emerging technologies of augmented and mixed reality, which enable new forms of knowing the surrounding world. This phenomenon manifests another characteristic of digital society – a blurred distinction between reality and virtuality (Ess, 2015).

Within digital society, people have begun perceiving themselves as "informational organisms (inforgs), mutually connected and embedded in an informational environment (the infosphere)" (Floridi, 2014, p. 94). The concept of inforg includes not only humans but also specific informational artifacts that are able to communicate with people and even demonstrate elements of social behavior. The emerging cyber-physical systems (CPS) comprise an example of such informational artifacts, since they are hybrid systems that can be considered neither purely artificial nor purely natural. Indeed, as advanced computer-embedded systems, CPSs demonstrate one of the characteristics of digital society whereby the boundaries between people, artifacts, and nature are blurring (Ess, 2015).

Obviously, the above transformations involving such fundamental features of the human being (the emergence of the informational abundance, transforming ways of observation of the world, and a changing view on the nature of surrounding objects) could not possibly leave unchanged key components of human culture such as scientific inquiry. Needless to say, scientific experiments are changing with emerging technologies; this change contributes to an epistemological breakthrough and to the construction of knowledge (Ganascia, 2008).

In this Chapter, we address the ways in which scientists obtain new knowledge and how these new methods affect science education. We focus on the classical triad of experimental research, 'subject-instrument-object,' and study the triad in its evolution into a so-called *digital triad* corresponding to digital society. We show that the digital triad parts from the classical triad in three ways: (1) it places the subject in the role of a new type of researcher – a digital scholar and an informational organism; (2) the digital triad's emerging experimental instruments are based on mobile, wearable and mixed-reality technologies; and (3) a new type of digital objects has emerged – namely, hybrid natural-artificial objects. We apply this proposed interpretation of the digital triad to study present transformations in inquiry-based science education. We also discuss how digital transformations are manifested in certain educational ventures by analyzing a number of pioneer projects.

The Chapter is organized as follows. In the Background section, some philosophical issues connected with the Nature of Technology and the Nature of Science are discussed. In section "The research triad", the experimental research triad and its evolution are presented. Then, the detailed description of the digital triad and the interrelations 'subject-instrument-object' in digital triad are discussed. The section "The digital triad in science education" is devoted to the digital triad in inquiry-based science education. A number of educational projects that utilize the digital triad are presented. Each project demonstrates changes in a specific component of the triad.

BACKGROUND

The Nature of Technology in the Experimental Science Context

In this Chapter, we focus on experimental science that generally accumulates knowledge by controlled experimentation involving manipulation of the study objects (as per Cleland, 2002; Cartwright, 1999). Traditionally, experimental science is considered to aim towards the generation of reliable knowledge of the world. According to such an approach, technological instrumentation plays a secondary, auxiliary role in experimental science. However, the development of experimental science has been intricately interwoven with the development of technology. Indeed, experimental science extensively relies on technological equipment, and resultantly, experimental research often contributes to technological innovations (Radder, 2009). Moreover, substantial conceptual similarities exist between the realization of experimental methods and that of technological processes, most significant of which is the implied possibility and necessity of manipulating and controlling natural objects. As such, scientific experimentation undergoes fundamental changes in the digital epoch. To understand the nature of experimentation and the manner in which it is affected by the digital era, we must comprehend the nature of technology and its interrelations with experimental science.

The most popular view on the role of technology in science considers technology as instrumental, as a tool enhancing scientific experimentation by improving human sensing capacities. Martin Heidegger (1954) criticized the instrumental view of technology as inadequate, in that it overlooks technology's essence. Gilbert Simondon (1958) explained the fallacy of the pure instrumental perception of technology and pointed out that a technological object is a component of so-called technicity. The technicity includes, along with the object, also human technical activities (work) (Simondon, 1958).

Questions about the nature of technology were profoundly explored throughout the twentieth century. Remarkable philosophers such as Lewis Mumford, Oswald Spengler, José Ortega y Gasset, Martin Heidegger, Gilbert Simondon yielded breakthroughs in our understandings of technology's role and nature. However, the impact of their notions remained restricted to the narrow circle of the academic community. At the level of broad social consciousness, the instrumental perception of technology remained intact; ultimately, technology is considered a tool.

The alternative, non-instrumental view of technology was unpopular in the industrial era, when technology was perceived dominantly as an 'applied science' (Gil-Peretz et al., 2005). This perception began changing with the advent of the digital epoch. When mobile, wearable, cloud, and other technologies began emerging in all spheres of life – and with the advent of concepts such as context awareness, social awareness, and ubiquitous computing – the instrumental perception of technology has become overly simple and inadequate.

Alongside the instrumental approach, another classical approach to technology is a so-called autonomous one (Peters, 2006), according to which, technology evolves by its own internal principles independently of surrounding world. One consequence of the autonomous approach was the perception of artificial technological objects as inorganic ones which may even contradict to human culture. Simondon (1958) argued that there is no conflict between technical artifacts and human culture. Humans and technical artifacts coexist. Moreover, "…humans are the conductors in the world-orchestra of technical artifacts" (Simondon, 1958, p. 11). Additionally, Simondon defines an artifact not just as an entity but as an evolution process. He "used the word 'objet' for indicating a process rather than a device or machine" (De Vries, 1998). Such dynamic and evolving perception of the artificial object, which is traditionally considered as a static and unchangeable, is highly impactful.

Another traditional approach to technology is the reflective one. The "reflective philosophy of technology sees as its task the study, analysis and evaluation of technology and its relation to society and the human condition" (Brey, 2014, p. 129). Those holding the reflective perspective consider technology to be something created by professionals and unchangeable by users. In contrast, supporters of the constructive philosophy of technology advocate "the development of philosophical approaches to guide and transform the practices of those actors in society that are responsible for the development, regulation and use of technology" (Brey, 2014, p. 129). Technological constructivism emphasizes the global qualities of emerging technologies – their openness, configurability, and availability. Indeed, constructivism is connected to the 'science-as-technology' notion: according to that concept, the old dictum: 'science discovers, technology invents' should be replaced with, 'science discovers because it invents' (Lelas, 1993). As such, scientific theory becomes an instrument of design, while technology itself becomes the object of research.

We argue that in digital society, experimental science will evolve against the background of the *non-instrumental, non-autonomous* and *constructive* approach to the nature of technology. Moreover, our analysis of important changes in technology and in the philosophical understanding of its role in the experimental science taking place within digital society reveals that to complete the general picture, a particular emerging epistemological issue must be taken into account.

Namely, the need exists to rethink the concept of scientific collaboration and its role in science. The commonly acknowledged status of scientific collaboration as one of the key characteristics of contemporary science is based on the two following conditions:

1. *The significance of scientific collaboration as an integral part of research*. Presently, scientific collaboration is not only considered a way of distributing knowledge, but also constitutes knowledge itself (Nielsen, 2013). It is becoming a knowledge-making activity, which includes different types of communication: "communication among scientists is what makes knowledge possible" (Nielsen, 2013, p. 2081).
2. *The phenomenon of data abundance followed by the emergence of a new phenomenon of Data Intensive Science*. Recently, a number of new methods of collection and analysis of scientific data have yielded substantial progress in research practices. Philosophers of science and many scientists have noted the recent qualitative progress in the methodology of scientific research (Hey, Tanslev, & Tolle, 2009). They characterize this progress as leading to a new 'data-intensive science' research paradigm.

The emerging research field positioned at the intersection of scientific experiment and digital technologies will inevitably include the fundamental topics of both the Nature of Technology and the Nature of Science. In the present section, we claim that for studying this emerging field one needs fresh philosophic approaches. Namely, the non-instrumental, non-autonomous and the constructive approaches of Nature of Technology were ahead of their time in the past, and the communication-centered approach of Nature of Science has been proposed quite recently. We consider that such approaches should be used together and are essential for studying the digitalization of experimental science.

THE RESEARCH TRIAD: SUBJECT-INSTRUMENT-OBJECT

As noted above, any traditional experimental scientific research comprises three fundamental components: (1) a research subject (researcher); (2) an instrument of research (experimental equipment); and (3) an object of research (natural objects, processes, or phenomena). This section focuses on the classical experimental triad, *subject-instrument-object*.

In the classical research triad, the only technological component is the second one, the instrument. The other two components are natural. Philosopher Luciano Floridi in his notion of 'technology as in-between' (Floridi, 2013), proposed a scheme of three orders classifying the relations between scientific research and technology. Under this scheme, the classical triad aligns with a 'scheme of the first order' ('nature-technology-nature'). Floridi considers technology to be an entity located between two others: (1) an interacting user, comprising the main actor in any technological phenomenon; and (2) what Floridi calls 'natural affordances,' which can be natural objects, processes, or phenomena. The second order in Floridi's scheme, 'nature-technology-technology,' corresponds with experiments in which a natural object is replaced by objects comprising an artificial portion. In the third and last order in his scheme ('technology-technology-technology'), the remaining non-technological component, the experimenter him or herself, becomes an artificial, automated knowing subject – something close to an artificial intelligent entity. In this last order, the humans are no longer in the scheme. The 'in-between' model provides just three possible schemes. Floridi proposes no scheme of the fourth order because "such a chain can always be reduced to a series of triples, each of which will be either of first-, of second-, or of third-order" (Floridi, 2014, p. 32).

In this Chapter, we apply the 'in-between' concept to study the digitalization of experimental science. We consider the research triad of the second order as a triad of the digital epoch, in contrast to the triad of the first order, which characterizes the epoch preceding the digital one. In other words, we distinguish two epochs in development of the experimental science triad: pre-digital and digital.

The pre-digital epoch relates to the longest period of history of science – from the emergence of empirical science at the end of XVI century through the beginning of the XXI century, when society's digital transformations commenced.

The digital epoch is the time when digital technologies become ubiquitous in human life and when these new emerging technologies demonstrate their qualitative difference from habitual technologies. This is an era in which society in general, and experimental science in particular, begins to change significantly. In conjunction, the non-instrumental and constructive approaches to technology become topical.

Notably, the transition from the pre-digital to the digital epoch was not instantaneous. A transition period emerged from the middle of the twentieth century (when information technologies just started to be used as experimental research instruments) through the present (when we witness the ubiquitous character of the digital technologies and their integration in all spheres of scientific research). The transition period has formed the first generation of researchers who used digital technologies in their research. Moreover, it provided both practical and theoretical basics of such integration.

The Research Triad in the Pre-Digital Epoch

The pre-digital epoch was characterized by experimental facilities, based on either analogous amplification of energy or transformation of energy. Various instruments (including scientific ones) that function on these principles played (and keep playing) an important role in human life. Technological apparatus such as the microscope, telescope, compass, timer, and other means of observation and measurement have become integral components of human culture throughout the span of history.

We argue that pre-digital technology naturally corresponds to humans' physical nature. Though the functional complexity of such instruments varies broadly, overall, humans consider these instruments to be quite natural and generally understandable. Instruments of the pre-digital epoch operate according to human notions of function; namely, according to analog principles. Such devices are relatively simple since they are based on linearity and continuity and facilitate processes of learning. The contemporary physicist John Barrow, in his book, "New Theories of Everything," notes:

Simple linear phenomena can be analyzed in pieces. The whole is nothing more than a sum of its parts according to this approach. Thus, we can understand something about a system without understanding everything about it. Non-linear chaotic systems are different. They require a knowledge of the whole in order to understand the parts because the whole amounts to more than the mere sum of its parts. (Barrow, 2007, pp. 147-148).

Social consciousness yielded greater awareness about the tight relations between technology and science. Such awareness resulted from the great progress in instrumentation based on energy transformation, which, in turn, created a view of technology as an applied science (Gil-Perez et al., 2005).

The pre-digital epoch – the longest stage of scientific technology development – forms the basis for understanding the processes of scientific research. As discussed above, the pre-digital triad reflects the first-order scheme of the 'in-between' approach. This traditional experimental research triad comprises: (1) the subject – a classical researcher who uses instrumental facilities for observations and experimentations; (2) the instrument – experimental facilities based on analogous amplification and/ or transformation of energy; and (3) the object – natural objects/phenomena.

When defining the pre-digital epoch triad, it is not sufficient just to define the entities comprising the triad (subject, instrument and object). Clarifying interrelations among the entities are needed. The relation "subject-instrument" is clearly instrumental, since the instrument is a technological artifact, which functioning is based on physical principles and energy transformation. The relation "instrument-object" is mediated by a subject during an experimental research process. Both the research process and the instrument are components of the "technicity" (Simondon, 1958), the practical sphere of the experimental research.

As we discuss below, the digital triad has transformed each of the components, creating a more complex formula of scientific experimentation.

The Research Triad in the Transitional Period

The digital triad did not replace the traditional research triad instantly; rather, a transitional process emerged alongside developments in digital technology. Thus, we can point to a transitional period between classical scientific research and the digital reality in which scientific inquiry is conducted at present.

The transition period in the history of the research triad commenced when instruments began functioning on the principle of transforming information, in addition to transforming energy. The first devices of this kind were digital computers invented in the middle of the twentieth century. In the 1950s, computers had no relation to scientific research. They were used mostly for various calculations. This situation changed in the early 1960s, when the first mini-computers based on transistors were invented. Those computers were: (a) relatively miniature, and thus could be physically placed in an experimental laboratory; and (b) were capable of working under a 'real time' regime, which enabled them to be connected to the experimental equipment.

The next serious step in the scientific use of informational technologies was the invention of the microprocessor, followed by the creation of a personal computer in the mid-1970s. Since then, scientists have nearly universally come to appreciate the efficiency of microprocessor-based devices. Microprocessors have become an integral part of any innovative scientific equipment. "In this day and age very few real experiments are conducted without employing the latest technology – sophisticated measurement instruments supplying large amounts of accurate data to a computer for storage, analysis and display" (MacKenzie, 1988, p.13).

Simultaneously, innovative computer literacy skills become mandatory components of scientists' background. This trend has become even more noticeable in the mid-1990s, following the emergence and broad expansion of the Internet. Scientists have finally obtained essential informational support in their research.

Notwithstanding the intensive development of informational technologies and their dissemination in scientific research, the role of technology in experimental science did not change during the transition period. Technology remained just a means intended to improve a scientist's work by taking on some routine of the scientific research and by intensifying the scientist's work. Correspondingly, interrelations between components of the triad are not being changed in the transition epoch. Using a terminology introduced by Floridi, one can call the transition period as the period of technology enhancing but not augmenting the technology (Floridi, 2014, p.89).

The situation changed again around 2005, with the advent of the digital epoch. Indeed, the change was followed by intensive development of informational technologies. Notably, we must consider transformations in scientific research of the digital epoch as a part of the global transformations of human society in this era.

THE RESEARCH TRIAD IN THE DIGITAL EPOCH

As noted in the Introduction, the main symptomatic transformations of the digital epoch are the following: (a) a blurred distinction between reality and virtuality; (b) further blurry distinctions between people, nature, and artifacts; and (c) a reversal from scarcity to abundance of information. In this section, we define the research triad of the digital epoch and demonstrate how the components of the triad reflect the era's social transformations. For simplicity, we refer to the research triad of the digital epoch as the *digital triad*.

The Experimental Researcher of the Digital Triad

The first component of the triad, the experimental subject/researcher, has altogether transformed in the digital epoch. This is not to say that the classical scientist is extinct. Merely, alongside researchers of the classical type, a new type of researchers has appeared.

First of all, such new researchers are inhabitants of the digital society; they are inforgs living in active harmony with the informational environment of digital society. We call such new researchers 'researcher-inforgs'. Their scientific activities are digitally inspired, including intensive collaboration and data exchanges with colleagues, experimental research based on analysis of 'big data,' use of digital curation, and other emerging scientific undertakings.

Moreover, the professional identities of such researchers are expressed in the virtual space. Their collaboration with their colleagues and research assistants takes place mainly online. Indeed, science nowadays is increasingly collaborative (Nielsen, 2013; Olson, Zimmerman & Bos, 2008). Whereas in the past, scientific collaboration required that scientists share the same physical place, contemporary communication technologies enable cooperation among scientists from distant institutions and different disciplines. Thus, scientific research has become both data-intensive and highly dependent on intensive communications. Many web-based resources supporting experimental research become available. The new researchers of the digital epoch are able to integrate raw data received from different resources into their own research, applying big data analysis and network analytic methods. As a result, their research success depends on how well they collaborate with colleagues and apply technologies in emerging areas including databases, visualization, and cloud computing.

The new researcher-inforg reflects one of the global transformations of digital society: a reversal from scarcity to abundance of information. Indeed, informational abundance enables the researcher's transformation from a traditional knowing subject into a new researcher who utilizes a plurality of sources and applies informational technologies for comparing, transforming, analyzing, and demonstrating results.

Cloud computing is among the key technologies supporting the above-mentioned innovations in scientific research and supporting the researcher-inforg. Mell (2011, p. 2) defines cloud computing as "a model for ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction." Floridi considers cloud computing as the first "graceful step out of the idea that computers need humans" (as cited in Miller, 2010, p. 4). Cloud computing resources are remote and independent from their users. The fact that both personal and public data is stored in the cloud changes fundamental views about ownership, accessibility, and usefulness of information and knowledge. These changes are critical in transforming the researcher into the researcher-inforg.

Experimental Instruments of the Digital Triad

The second component of the digital triad – the instrument – is also changing significantly. As is the case with the researcher, the emergence of instruments of a new nature coexists with the ongoing use of traditional experimental equipment.

Several scholars have proposed classifications of scientific instruments. Radder (2009) offered a distinction between instruments that represent a natural property by measuring its value (e.g., a device that registers blood pressure), instruments that create phenomena that do not exist in nature (e.g., a laser), and instruments that closely imitate natural processes in the laboratory (e.g., an Atwood machine, which mimics processes and properties of falling objects).

Measurement in particular has changed in the digital epoch, with the emergence of a so-called sensor revolution. The emerging smart sensors are not merely measurement devices in the traditional sense, which can transfer a value of a specific parameter from an object to the researcher by performing analog to digital transformation. The new sensors, interconnected online, are adapted to receive and/or process information from a cloud memory and other resources, so as to provide the researcher with the desirable meaningful data beyond just rough values.

The kind of scientific instruments that create non-existing phenomena can be upgraded by emerging technologies that provide computer simulations of the non-existing phenomena. A number of scholars even distinguish computer simulation and modeling from the empirical research, considering such modeling and simulation a substantive experimental research paradigm in its own right (Hey et al., 2009).

The instruments imitating natural processes utilize the emerging digital facilities and form a new type of instruments – mixed-reality devices. Mixed reality lets the user observe the real world while also recognizing in it some (believable) virtual objects. The mixed reality device anchors those virtual objects to a point in real space, making it possible to treat them as real.

Among the emerging technologies supporting the above-mentioned innovations are mobile and wearable devices, as well as ubiquitous computing. Such technologies include context-aware computing, ubiquitous wireless networks, smart objects, and location-based systems. Ubiquitous computing involves the most natural possible interaction between a user and a computer, geared towards the ultimate aim of the user not even realizing that s/he is interacting with a system (Kwok, Cheng, Ho-Shing Ip, & Kong, 2011).

Such new instruments based on mobile and wearable technologies, have transformed to comprise a new entity. The new entity, being different from the habitual instrument, does not just enhance it, but (and which is especially significant) - augments it. Indeed, new instruments that include virtual components, reflect one of the transformations of the digital epoch – a blurred distinction between reality and virtuality.

The Research Object of the Digital Triad

We argue that the third component of the digital triad – the research object – is no longer purely natural. The new object of research may be comprised of an artificial portion, which is mainly a digital one. In other words, the object becomes a hybrid one with functions partially based on natural laws and partially grounded in the technological specification of the digital devise embedded within it.

One of the clear manifestations of the new object of research is emergence of a cyber-physical system (CPS). CPSs are hybrid natural/artificial systems that humans create by providing systems with an ability to behave socially. The emergence of the CPS is an important cultural phenomenon of digital society (Levin, 2016). CPSs comprise an example of objects that cannot be attributed to either nature or technology, since they contain both natural and artificial components.

Indeed, CPSs' integrated computational and physical capabilities enable interaction with humans through many new modalities. The ability to interact with and expand the capabilities of the physical world through computation, communication, and control is a key enabler for future technology developments (Baheti, 2011). CPSs represent a specific branch of complex technical systems' confluences of knowledge and computing technologies; networking and informing; and physical artefacts and engineered systems – towards operating and servicing in human and social contexts. CPSs are artifacts with characteristics that allow them to be inhabitants of the newly recognized infosphere – alongside humans (Vroom & Horvath, 2014).

Humans behave as informational beings not only in cyberspace, but also (even more so) in reality. 'Reality' changes permanently by accommodating more and more other informational entities, which, in turn, may also serve as artifacts. Awareness of such a previously unexpected phenomenon is an important feature of the digital epoch. People interact with means of digital communication socially. This interaction takes place even if people do not perceive the communication means, programs, and media agents as partners in their frame of their socialization.

CPSs reflect a key transformation of digital society: a blurred distinction between people, nature, and artifacts. As Bernadette Bensaude-Vincent and Bill Newman (2007, p.2) note, "instead of opting for an absolute distinction of quality between the artificial and the natural, one should accept only a gradual distinction of degree."

In this section, we have shown that all three components of the digital triad are different from their corresponding ones in classical experimental science. To sum, in the digital triad: (1) the subject is a researcher-inforg; (2) the instrument is based on emerging mobile, wearable, and mixed-reality technologies; and (3) the research object involves hybrid natural/artificial systems.

Interrelations Subject-Instrument-Object in Digital Triad

The relation Subject-Instrument of the Digital Triad is a relation between the researcher-inforg and the instruments based on the above-mentioned emerging technologies. This relation can be clarified by using the Simondon's concept of "trans-individualization" (1958). Particularly, mobile and wearable devices provide a bright example of the trans-individualization. Indeed, each device is absolutely equal to all others as a figure (form) but, being totally individualized, absolutely different as a ground (content).

The relation Instrument-Object of the Digital Triad is not a simple relation between the above-mentioned augmented instrument and said hybrid natural/artificial system. This relation is sophisticated since it includes a researcher as a mediator. Obviously, such relations are not yet studied enough, and undoubtedly represent a rich field for a highly topical research.

THE DIGITAL TRIAD IN SCIENCE EDUCATION

In the previous sections, the research triad was considered as a model of the experimental scientific research which is traditionally plays a central role in science education. Namely, a school science laboratory constitutes a classical and highly important educational environment. Thus, an idea to utilize the digital research triad in class of the Digital society looks highly justified. In turn, in a science class, the research triad is reflected in inquiry-based science education. In this section, we consider students as subjects of the triad that engage in inquiry-type investigational activities.

The research triad has been evolving alongside a number of reforms in science education. First, the triad appeared at the time of the 'Sputnik' reforms, when Schwab (1960; 1962) suggested that science must be taught in a manner that is consistent with the way science operates – namely, "in an inquiry format" (Barrow, 2006, p. 266). Since then, a number of policy documents emphasize that students should develop the abilities necessary to conduct inquiry (AAAS, 1993); have a fundamental understanding about specific characteristics of scientific inquiry (NRC, 2000); and engage in scientific practices and methods of investigation used by scientists (NRC, 2012).

As such, the concept of scientific experimentation for the sake of learning is considered as inseparable part of science education for over 60 years. Below, we discuss the implications of the digital triad for inquiry-based science instruction.

The Research Triad in Inquiry-Based Science Class

Historically, in the pre-digital epoch, the research triad in a science class was shaped as Floridi's first order scheme. Students *(subjects of the triad)* conducted hands-on investigation of natural phenomena (*object of the triad)* in a lab or field, by utilizing equipment (*instruments of the triad*) based on energy amplification or transformation. This type of investigation still comprises a significant and inseparable part of the science curriculum in various countries (Abd-el-Khalick et al., 2004).

The transition period (between pre-digital and digital epochs) in a science class was characterized by emerging of Microcomputer-Based Labs (MBL) – namely, labs utilizing various probes and sensors for performing various hands-on inquiries. A number of successful educational inquiry-based projects emerged at the turn of the century: The Global Lab Project (Berenfeld, 1999; 2010), the CoVis Project (Pea et al., 1997; Pea, 2002), and the GLOBE Project (Penuel & Means, 2004). Empirical research of these projects focused mainly on the *instrumental* component of the triad and on the effect of innovative inquiry activities on students' outcomes (such as their learning of scientific concepts, inquiry skills, and understanding of the nature of science). Specific aspects of MBL technology such as real-time graphing (Nicolaou, Nicolaidou, Zacharia, & Constantinou, 2007; Pierri, Karatrantou, & Panagiotakopoulos, 2008); collaborative data visualization (Pea, 2002; Penuel & Means, 2004); and collaborative data acquisition, sharing, and analysis (Berenfeld, 2010) were reported. As a next stage, MBL technologies became broadly applied in different combinations of physical and virtual labs. These initiatives included sequentially combined labs; blended physical and virtual parts of labs with selected affordances associated with certain learning objectives; labs run in parallel, such that virtual and physical labs are available at the same time; and connected physical and virtual labs whose findings are compared. Combining physical and virtual labs became a popular and highly acceptable educational practice, providing students with a profound understanding of certain scientific topics (Chao, Chiu, DeJaegher, & Pan, 2016; De Jong, Linn, & Zacharia, 2013).

Since science classes began functioning through the digital triad, most studies evaluating the phenomenon focused on the instrument component. Two systematic reviews of the use of mobile technologies in education have indicated that the majority of the studies on the matter focused on designing systems, followed by evaluating the effectiveness of such systems (Crompton, Burke, Gregory & Grabe, 2016; Wu et al., 2012).

One of the important MBL innovations in the digital epoch is mixed reality technology (Concord Consortium, 2012). Indeed, different types of the inquiry activities based on mixed-reality technologies were introduced into science education, including augmented reality lab/field inquiry utilizing real phenomena augmented by virtual images and augmented virtual labs with embedded virtual phenomena in real, physical space and time (Chao, Chiu, DeJaegher, & Pan, 2016). Such inquiry enables students to perform scientific experiments that they cannot easily perform in the real world (Klopfer & Squire, 2008), to visualize concepts such as airflow or magnetic fields, and to experience events by displaying virtual elements over real objects (Dunleavy, Dede, & Mitchell, 2009; Wu et al., 2013).

As noted above, mobile and wearable technologies also comprise some of the key developments of the digital epoch, and have already been broadly integrated into inquiry-based science learning. A number of studies report using mobile and wearable technologies as measurement devices within science education (e.g. Gonzales et al., 2015; Gómez-Tejedor, Castro-Palacio, & Monsoriu, 2014; Hochberg, Gröber, Kuhn, & Müller, 2014; Kuhn & Vogt, 2013). Measurement with such technologies can be performed by using a variety of sensors, utilizing either standard applications or ad-hoc ones. Bracelet products such as Fitbit, Garmin, and Striiv enable the measurement of motion and vital signs, giving rise to the 'quantified self' phenomenon (Van't Hooft, Swan, Cook, & Lin, 2007). These products provide wireless connectivity, on-board analytics, and interfaces for hands-free feedback that provide educators with a wide range of opportunities in conducting experiment-based training.

Yet the use of mobile and wearable technologies is not limited to their measurement features. The use of mobile technology in science education has been studied also in the context of scaffolding, location-aware functionality, visual/audio representations, digital knowledge-construction tools, and digital knowledge-sharing mechanisms (Zydney & Warner, 2016). A number of characteristic features of wearable technologies (e.g. Google Glass) were studied in this regard: interactive sight and manipulation, including virtual representations (simulations) of physical phenomena simultaneously with corresponding virtual phenomena (Lukowicz et al., 2015); recording and providing a feedback (Coffman & Klinger, 2015), communication and distribution of resources (Bower & Sturman, 2015); and hands-free access and first-person view (Wu et al., 2014).

Regarding the *subjects* of the digital triad (students), studies have focused on the expanding scope of students' inquiry activities via online communication, use of big data, and participation in forums and networks. The main focus of studies to date has been on technology use in collaborative, inquiry-based science learning, and the general conclusion seems to be that "using collaborative technologies can help support collaborative inquiry within science education and can help model how scientists use technology" (Donna, 2013, p. 2). Likewise, scholars noted that "collaboration is very natural to real scientific inquiry, so the introduction of collaboration into the learning process brings the learning environment closer to real inquiry" (Van Joolingen, De Jong & Dimitrakopoulou, 2007, pp. 114-115). Specifically, studies of instrumentation of the digital triad in the classroom have investigated issues involving collaborative inquiry argumentation (Laru, Järvelä, & Clariana, 2012; Raes, Schellens, & De Wever, 2014); and brainstorming, reflective writing, feedback, interacting dialogue (Donna & Miller, 2013; Hwang, Tsai, Chu, Kinshu, & Chen, 2012).

Notably, the *object* component of the digital triad has been studied to a much lesser extent; only one educational project seems to have been reported about in this regard – a so-called Connected Gardening project (Zuiker & Wright, 2015), which utilizes cyber-physical systems as objects of the inquiry. We expect inquiry into this field to expand in upcoming years as use of the digital triad in inquiry-based learning continues to grow.

The Digital Triad in Educational Projects: A Few Case Studies

In this section, we analyze three educational inquiry-based science projects in the context of the digital triad. We trace how specific emerging technologies implement the above-mentioned transformations in science education.

The first project involves a location-based, augmented reality environment with a five-step guiding mechanism custom-developed so as to guide students in sharing knowledge during inquiry-based learning (Chiang, Yang, & Hwang, 2014). In this project, fourth-grade students from an elementary school in North Taiwan studied the ecological environment at a nearby pond. Specifically, students physically observed the habitats and morphology of selected aquatic plants by using a location-based Augmented Reality (AR) system based on a five-step activity series: 'ask,' 'investigate,' 'create,' discuss,' and 'reflect.'

At the 'ask' stage, the students were capable of: (1) using custom-tailored devices to take photos in order to discover and to observe aquatic plants; (2) expressing their observations and inquiries through various designs; (3) adding text and supplementing pictures; (4) sharing pictures and text messages through the location-based AR interface.

At the 'investigate' and 'create' stages, the students could browse information that they and their peers shared in posts on the targeted platform. They could also activate the text or pictures shared by their peers to learn more or use verbal descriptions to understand the knowledge that the sharer of this content wished to convey. They could then send textual questions and visual or verbal descriptions to study or enhance the data provided by their peers.

At the 'discuss' and 'reflect' stages, many students formed subgroups in chat rooms to focus on a particular topic and became engaged in communication and discussion. Through the platform, the students could ask questions, participate in discussions, and think cooperatively, which led them to discuss additional questions and to make additional inquiries.

This project clearly illustrates changes that take place at the *subject* component of the digital triad, associated with a high level of inquiry-oriented student collaboration. Such effective collaboration proved possible due to the abundance and availability of scientific knowledge regarding to the learning topic. Notably, this knowledge is highly relevant to the object of inquiry, while also reflecting the personalities of the research subjects (the students). Through such inquiry-based learning processes, students form their own online personalities as researcher-inforgs – researcher connected by a network. New technologies have enabled this innovative learning activity – above all, the emerging communication technologies and cloud technologies playing a revolutionary role in today's scientific inquiry.

The second project is the 'G-Physics' program, which utilizes a Google Glass application for a standard high school acoustics experiment: determining the relationship between the tone frequency generated by hitting a glass filled with water and the amount of water in the glass (Lukowicz et al., 2015). The project requires that students conduct experiments interactively, that they manipulate the theoretical representation of the relevant phenomena, and, simultaneously, that they interact with real-world phenomena. The inquiry activities in this project mainly involve the *instrumental* component of the digital triad. The use of Google Glass as a virtual component in the study enables research regarding multiple objects by observing and manipulating them in reality and by enhancing the inquiry virtually.

Finally, the Connected Gardening Project (Zuiker & Wright, 2015) reflects the changes of interest in the *object* component of the triad. In this project, a fourth-grade class organizes and refines its garden plot using observations of the physical environment and evaluations of data from a networked digital probe. In this way, the probe and the plot together form at least one specific cyber-physical system that visualizes and provides access to some parameters of the garden's soil, water, and sunlight. In turn, the data further allows students to display the garden system according to its underlying physical markers of plants growth, as well as to experience the patterns and processes involved in dynamically balancing the garden system.

This program is based on the ability of the plants, by means of the various sensors they were attached to, to transfer data both between the objects and from the objects to the cloud memory. Hence, the main feature of the project is the fact that the objects (the plants in the garden) are no longer the purely natural entities they would have been in the pre-digital epoch. As CPSs, these objects are hybrid natural-artificial systems that are able to transfer a substantial amount of data. Moreover, the objects demonstrate some basic social behavior. The emergence and use of such hybrid systems as the objects of scientific inquiry is unprecedented in science education.

FUTURE RESEARCH DIRECTIONS

The proposed triad-based approach relates both to the foundations of experimental science, and to science education in digital epoch. In both of them, there are a number of highly desired research directions. The proposed idea of the triad evolution from a pre-digital to a digital period is just the very beginning of a deeper and wider study of the triad and its evolution. The proposed model has to be studied in the fields of: Nature of Technology, Nature of Science and Science Education.

In the fields of the Nature of Technology and the Nature of Science, the future study will relate to each component of the triad (researcher-inforg, augmented instrument and hybrid system). Approaches of such philosophers as Simondon, Rabardel, Floridi, Brey, De Vries, Feenberg can be useful in this research. In particular, Simondon's "trans-individualization", his theory of the technological artifact and his perception of cybernetics may be highly applicable.

In the field of Science Education, the future study may include the research of a new, digital pedagogics based on the digital research triad. We hypothesize that the digital triad is a new technological and educational entity, which must be considered as not a straightforward enhancement of the traditional triad. Consequently, a number of emerging pedagogical phenomena can be detected and studied.

CONCLUSION

This Chapter discusses some of the research that has arisen at the intersection of areas of scientific experiment and emerging digital technologies. This intersection represents a fascinating new field that deals with the nature of experimental science, the nature of digital technology, and the interrelations between experimental science and digital technologies.

Axiomatically, the *subject-instrument-object* triad comprises the core foundation of experimental science. The intrinsic presence of technological components as integral parts of the triad has transformed the triad in the new digital environment, in turn stimulating the study of these changes. We have shown that the experimental digital triad is different from the classical triad of the pre-digital epoch. Each component of the digital triad is enriched by particular features that are specific to the digital epoch: intensive communication as a feature of the research subject, virtualization as a feature of the research instrument, and not merely physical but rather hybrid features of the emerging research objects. Changes in each component of the triad reflect fundamental transformations of the digital epoch.

Our interpretation of the digital triad paves the way for understanding digitalization of experimental science in general. This understanding is based on the non-instrumental and constructive approach to the nature of the technology, as well as on awareness of the significant role of communication in scientific research.

The digital triad is integrated into science education in the form of inquiry-based learning activities. New hyper-connected students (researchers), digital instruments, and hybrid research objects are gradually introduced into educational institutions. A number of successful, innovative educational projects confirm this transformation.

The main contribution of our Chapter lies in its proposed approach towards the analysis of transformations in experimental science. Applying this approach in analyzing the digitalization of contemporary scientific research will yield understandings regarding both experimental science and science education. Moreover, the proposed approach has both theoretical and practical significance. This new method provides a theoretical framework for the study of digital transformations in experimental science and inquiry-based science education, while also serving as a practical tool for the assessment of innovative educational practices.

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KEY TERMS AND DEFINITIONS

Cyber-Physical Systems: A specific branch of complex technological systems comprising knowledge and technologies of computing, networking and communication, and those of physical artifacts and engineered systems towards operating and servicing in human and social contexts.

Data Intensive Science: The fourth paradigm of science after the three known paradigms of empirical, theoretical, and computational science. It is a data-driven style of science, where ICT is used to manage, analyze, and share data.

Digital Era: A period in human history characterized by the shift from traditional industry to economy based on ICT.

Digital Society: A society corresponding to the Digital Era in human history. It is the ICT dependent society, where the creation, distribution, use, integration and manipulation of information becomes the main economic, political, and cultural activity.

Experimental Science: A branch of science based on the empirical science research paradigm, which utilizes the gathering knowledge obtained by controlled experimentation, in which natural phenomena are manipulated in order to discover the unknown phenomena or test a known one.

Inquiry-Based Science Teaching: A plurality of methods and environments, which allow students to consider problems and situations scientifically by actually being involved in research process.

Nature of Science: An academic field that deals with methodological, epistemological, and ontological issues of science, including science knowledge, science limits, tools, products of science and human elements of science.

Nature of Technology: An academic field dealing with the essence of technology, its inherent biases, the questions how individuals and society direct, react and changed by technology as well as its implications for education.

Research Triad: A theoretical model of the experimental scientific research, which comprises: (1) a research subject (researcher); (2) an instrument of research (experimental equipment); and (3) an object of research.

Scientific Inquiry: The diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. It defines in terms of two dimensions: (1) scientific ways of knowing and (2) a way of learning science.