ROLES OF DIGITAL TECHNOLOGIES IN EDUCATION: FROM COMPUTERS IN CLASSROOMS TO DIGITAL KNOWLEDGE BUILDING ENVIRONMENTS

M. Herczeg

University of Lübeck (GERMANY)

Abstract

Due to technological developments, the future of education has often been discussed with dramatic visions. In the 1960s, it was debated whether computers would replace teachers in classrooms. In the 1970s, more concrete visions came up with expensive solutions in form of large mainframe computers with interactive terminals connected to digital learning libraries. In the 1980s, it was expected that the emerging personal computers would individualize education. Around the year 2000, the Internet came along for the public with Wikipedia and other information sources that again questioned the importance of books and teachers. The next step have been mobile computer systems that basically enabled contextualized authentic learning outside of school with ubiquitous Internet-based information access and even digital information augmentation of the physical world. And today, many believe that it will be generative artificial intelligence systems that will fundamentally and rapidly change the world of education. This contribution reflects this history and likely future of digital educational technologies to discuss why some of them succeeded and others failed. Through a generalization of digital learning technologies, the strengths and weaknesses of such technologies in supporting learning processes in an increasingly complex world are characterized. From there, promising computer capabilities for future educational technologies are combined, leading to what we will call Knowledge Media Machines and Digital Knowledge Building Environments mainly based on post-constructivist theories. Finally, the prototypical system Ambient Learning Spaces (ALS) is outlined that has been developed and evaluated in a research project for over more than a decade.

Keywords: Technologies for Learning, Learning Environments, Artificial Intelligence, Knowledge Building, Post-Constructivism, Ambient Learning Spaces.

1 INTRODUCTION

The discussion about the future of education has often been triggered and driven by technologies, especially digital technologies such as computers, digital networks, interaction devices and information platforms. It is interesting to analyze the results of some of the seemingly most important technological developments for education, trends and forecasts to identify goals and solutions that offer high potential for future educational methods and infrastructures.

2 EDUCATIONAL TECHNOLOGIES OF THE PAST

The evolution of educational technologies gave rise to several disruptive technologies that were considered important steps to significantly change the world of education. We will review some of the most revolutionary technologies of their time and discuss their potentials and misconceptions.

2.1 Computers – Getting Rid of the Teachers

In the 1960s we had the excited discussion, whether teachers will be replaced in the classrooms by computers: The computers were expected be intelligent question, answering and guiding machines, in some way just like teachers.

A note published by Gay Gaer Luce with the title *“Can machines replace teachers”* [1]: *“Ready or not, however, it seems to be coming.”* was refering observations like *“Specialists calculate that schools will need one machine or or programmed text for about every three students, and that automatic instruction will occupy between a fifth and a third of each school day”*. Even when there were no serious scenarios about a computer managing a school class, many people just believed in such a development because computers seemed to be so incredible performant, knowleageable and even intelligent. Compared to todays computer performance, those computers were just first simple programmable systems with less

ISBN: 978-84-09-63010-3

performance than a current digital alarm clock. It seems that even well-educated people believe in the power of interactive machines, even if they show only basic logical and mathematical abilities but are intransparent enough.

2.2 Mainframes – Programmed Curricula and Interactive Content

In the 1970s, after large computer systems had made their way into big companies and public administrations, the same mainframe computers were used to implement digital learning platforms containing learning modules fitting some curriculum. It was called *Computer Aided Instruction (CAI)* and later *E-Learning.* The basic idea was to make any educational or even scientific subject available as a learning module on interactive computer terminals. Together with authoring systems for such modules, it seemed clear that it would only be a matter of time and diligence to complete and distribute these interactive libraries of human knowledge. Systems such as *PLATO (Programmed Logic for Automated Teaching Operation), PLANIT* or *IBM's Course Writer III* paved the way to high expectations for educational situations going even into business and industrial training [2].

A lot of content had been produced for such systems, but apart from some installations, not much happened to the educational world. Only simple text and graphic materials and some interactive labs had been created with high effort. Among other doubts, it seemed at least too expensive to create enough up-to-date content to fundamentally penetrate the educational system [2]. Therefore, digital content on such CAI or E-Learning platforms raised the question about who would be able and willing to create enough content of high acceptance and usability to spread into the large and slow educational systems. It seemed similar to the creation and distribution of textbooks and classical learning materials, but with much higher effort and cost.

2.3 Personal Computers – Individualizing Teaching and Learning

In the 1980s, it seemed that the new personal computers (PC) would be the game changer in education. Since every student would have their own PC, it seemed clear that we would no longer need expensive mainframe computers. At the same time, *Intelligent Tutoring Systems (ITS),* a type of *Artificial Intelligence (AI)* system, were being programmed to pave the way for computers that could answer questions, provide explanations and guide the student on a personal basis, much like the utopian ideas of computers as teachers in the 1960s. As an important consideration after many years of experimenting with PCs in real school environments, Alan Kay noted later, tempering expectations, *"We and […] were not trying to improve the already excellent school by introducing technology. We were trying to better understand the value computers rnight have as supporting media."* [3].

As a technological addition in the 1990s, CD-ROMs conquered the world of digital education as *Computer-Based Training (CBT).* Based on Multimedia PCs the curriculum was delivered to the students like the old school book did before. Millions of educational CD-ROMs, or later DVDs, were produced and piled up in homes, schools and universities. It became apparent that students quickly lost interest in this type of canned knowledge. In addition, there was a lack of viable business models to further develop and disseminate this method.

2.4 Internet – A Ubiquitous Network of Teachers, Learners and Knowledge

The situation changed dramatically in the next step around the year 2000, when the Internet became widely available. So the knowledge sources could be located in a network while the students had their computer at home or any other place. Physically canned content such as books or DVDs was no longer necessary. Going further than in schools, the Internet was used by universities to offer complete study programs over the network.

Soon, as the volume of content grew quickly and production costs were recognized as being high, the quality of learning materials deteriorated. Some ended up with study programs on more or less well produced PowerPoint® or PDF slides. Some programs delivered hypermedia web-based productions with content in media types such as graphics and video. It was called *Web-Based training (WBT)*.

Combined with WBT, teleteaching through video streaming was and is still practiced. So the classrooms and not the teachers have been replaced by computers. However, it does not seem that it would basically change the world of schools and universities. Learners become more or less free to choose the place of learning, and so are the teachers. This freedom has been evaluated during the COVID-19 pandemic and it shows that it works to some extent. However, a few years later, the big success is being questioned and many believe that the social aspect of learning is missing. The freedom to easily access the materials anytime and anywhere does not seem to outweigh the problem of being motivated to really learn without or with only some video contact to teachers or other learners.

2.5 Mobiles – Augmented Realities at Authentic Places

A few years later, stationary PCs were gradually replaced by a spectrum of different mobile computing devices like smartphones and tablets. Teachers and learners are principally able to teach anytime, anywhere, on “any computer device”. This basically enabled the learners to contextualize the learning process towards authentic places, like biotopes, urban spaces or production environments.

However, contexuatized computer-supported teaching is not practiced very often since the effort for the teachers and the mismatch of technologies, mainly platform and devices, is creating high challenges to teachers, learners and educational institutions.

2.6 Generative AI – Pattern Matching, Language Models and the Digital Parrot

Looking back at the former development steps of technology-based education, digital technology has not really changed most schools or higher education institutions so far. Nevertheless, ubiquitous computers in any form are used every day to read, write, present or communicate [4]. So is the long-term result that computers are used as everyday tools to replace classrooms, paper and pencil to some extent? And what happened to the teachers?

Interestingly, a new technological development seems to revolutionize everything that has been achieved so far. There appears to be an "emerging intelligence" on the network. Most people are not clear about where and how this is happening. *Generative AI,* like *ChatGPT* and similar systems, seems to finally close the full circle to the 1960s as intelligent question and answer machines with teaching functions, as Gay Gaer Luce put it: *“ready or not, it seems to be coming.”* [1]

Why are so many people excited or even convinced by the digital parrots like ChatGPT? Have they, like people in the 1960s and through the following decades, been fooled by a technology that was just not yet well understood or is it just a question of putting all of these technologies into their proper role working together?

3 THE ROLES OF DIGITAL TECHNOLOGIES IN EDUCATION

Considering human cognition along the layers of perception and activities can be used as a structure to discuss the roles and values of technologies. This has been done extensively in the work sciences, mainly industrial psychology and ergonomics, and can be applied to the learning processes as well.

3.1 Technologies for Perception, Memory and Articulation: I/O-Devices

It has been the computer display that drew much of the attention into digital educational technologies. First text-based, later the bitmap- and graphics-based displays have been able to present learning structure and content in a detailed, flexible and fast way. While paper-based books are linear and static, computer displays are kind of fluid when presenting information. Human perception can be stimulated by high resolution, color and multi-dimensional displays similar to a natural environment. Such computer devices can be used to simulate, replace or even deceive human perceptive processes on a high level of fidelity and therefore belief. Besides the visual channel, computers are able to stimulate the auditory and to a lower extent haptic and other sensual channels as well.

On the articulatory side computer technologies did not reach much more than keyboards, pointing devices and limited gesture input devices. As a result, the perceptional part of learning has been addressed quite well, while the articulatory part has always been weak and complicated. So computers have always been more information delivery technologies instead of reactive technologies. These needs and may be changed by future technologies.

3.2 Technologies for Structure: Symbols, Syntax and Grammar

A basic paradigm for computer systems has always been the *Calculator* or *“Number Cruncher”.* To go one step further, we had to recognize that computers are not only calculators but logic-based machines. This fitted quite well to the pedagogical theory of *Programmed Instruction,* which even led to the idea of replacing teachers by computers. Other computing paradigms for teaching and learning have been so-called *Production Systems* based on rules as well as *Grammars* to process or generate formal and natural languages.

To address the observation that human knowledge is often structured in a relational way, the early ideas of Vannevar Bush's *MEMEX* [5] as well as 50 years later the real *World Wide Web (WWW)* with the browser technologies reflected and supported the dynamic and associative nature of human memory. Such *Hypermedia* concepts and technologies were a main foundation to support associative knowledge construction which today can be found in the WWW and knowledge applications like the *Wikipedia* and other frame- and link-based repositories.

Meanwhile through *Large Language Models (LLMs)* and the use of probabilities over words and patterns of language computers are viewed to be intelligent by generating well formed texts or images from seeds (prompts) of information. The processing and generation of grammatical and probabilistic language is perfectly suited to assist humans in the creation of written sources through automatic spelling correction, translation or even text generation. This is basically what systems like ChatGPT or similar systems do with enormous computational effort. However, the results are only reflections of available textual or graphical human articulations and should not be confused with creative processes of generating meaningful new from existing knowledge. Current approaches are still at the level of words or symbols, syntax and grammar combined with syntactic probabilities that lack models of semantics and meaning and therefore have a high potential for deception ([6], [7]).

3.3 Technologies for Content: Curricula, Semantics and Objects

The human cognition is not just about structures and patterns. We perceive our environment as a world of *Things*. These *Things* or *Objects* have shape, color and many other properties. Beyond this, objects have meaning for us. They will be recognized, classified and evaluated. They set up a *System of Objects* that matches our perception and imagination [8]. Through the observation and the control of these objects we interact with our complex physical world.

It has been especially through computers that we extended the world of imagery like through books, paintings, music, movies and gaming. Today we are able to create dynamic *Virtual Worlds or Virtual Realities* through computers. Virtual Realities augmenting or mixing with the "real" world has already changed a lot. This goes far beyond new ways of just imagining things through the creation of *Hyperfiction* as worlds of imaginations that create similar and sometimes the same effects to humans as the physical world does. *Simulacra* are perceived as being true things that create a perceived and believed world beyond the real world [9].

Education is always to some extent simulating and thinking the nonexistent. The human mind is well prepared for simulations. We do this every moment before we act or communicate except when we just use highly trained reflexes. Therefore, computers are of great value as they stimulate and drive the imagination to help us to better understand the world, even when it is not present and physically graspable for the learner. However, at the same time we have to make clear and distinguishable what is real and what is imaginary. This means, that at the same time we use this ability of computer systems, we have to make sure that the users have enough understanding what computers can and can't do. What we therefore need is computer literacy in the sense of understanding existence, meaning and limits of simulacra and simulation [9].

3.4 Technologies for Intentions: Pragmatics and Reflection

A human being needs to be able to create and follow intentions, reflect the state of things and act in a pragmatic way. This is not the level of computer applications of today. Current computers can have plans, but do not have intentions like natural beings and are therefore not able to share and discuss them. It is important to distinguish between intentions and plans. Intentions can be incomplete, contradictory, even emotional and are not the same like procedures and sequences of activities.

However, this challenge is just open. In the world of industrial work we would appreciate computer support in simple as well as in critical tasks related to situations and intentions [10]. Translated into the needs of education, a computer assistant might help the learner keeping track of the curriculum, discover new interesting things, get reflections of what has been reached successfully or what was fun for the learner to create recommendations how to proceed. It is not the virtual world and it is not the generative AI system that today is able to support this active and challenging task. It is still the teacher in the widest sense, whether as parents or schoolteachers or masters in professional areas that guide learners along their way to understanding, capabilities, emotions and even excellence.

4 EDUCATIONAL TECHNOLOGIES FOR THE FUTURE

Following successes, failures or missing computer capabilities and roles that have been used for education so far, we can try to identify important concepts and chances for the future of learning and teaching.

4.1 Artificial Sensual Environments

The human perception is a low-level but fundamental ability to sense and act in our physical world. This is quite natural and not much needs to be added about this basic ability at this point. Besides the ability to perceive or simulate the physical environment, artificial media can be used to give access to virtual content that is beyond our physical world.

Augmenting or even replacing the real world to some extent, computer-based environments can create new perceptional and informational layers. These layers can be of virtual physical or of informational nature mainly using the visual and auditory perceptual channel. *Augmented, Mixed and Virtual Realities (AR, MR, VR)* have been successfully used in education [11].

When it comes to acting and articulating in such enriched worlds the availability and generality of such solutions for education is not well developed so far. What we need are frameworks and devices to enrich any physical situation with such layers. The current solutions like see trough AR glasses and VR HMDs are quite expensive and clumsy to use and cannot be expected to diffuse into standard educational contexts. As a possible mid-term solution, the use of personal smartphones and tablets has lower fidelity but leads to much higher availability. Standardization of methods and devices will be necessary for the wide and natural use of such important technologies in educational situations.

4.2 Grammars, Logic and Inference Engines

Computers as machines of logic can enrich digital worlds with structure, like mathmatics, grammars or logic derivations. Through this, unstructured content transforms into a system of cause and effect. Solutions can be automatically generated or proved according to rules and calculus.

Computers have always be used to represent and apply grammars, rule systems, mathmatical and logic derivations. This is of high importance since large parts of human language and knowledge are based on such models. However, currently there seems to be a basic misunderstanding about the power of such systems. Early AI systems used to be based on well-defined inference systems. They came in different shapes like rules, logic or probabilistic inference systems. Current so-called *Generative AI Systems* have mainly be based on probabilistic and pattern-matching methods using large information structures found in certain areas of the internet. This looks like machines generating new from available knowledge, but this is misleading. Grammars and probabilistic matching only imitates inferences of knowledge without being rooted in semantics. Therefore the results are not part of a sense-making environments as long as human beings do not examine but just consume the results as being facts. That makes generative AI just smart or magic like a mystic oracle impressing people because of its well developed structural and contextualized probabilistic pattern matching abilities, like applying grammar and filling the gaps with application data [12].

However, this currently misleading approach of generative AI could be very valuable, if used with the knowledge of what it can and what it can't do. Transforming texts with spelling or grammar correction or rough translations can be very helpful not only in education, but it has to be combined with semantic models to climb to the levels of what we call human knowledge.

4.3 Semantic Models

Information models and grammars are just symbol systems without inherent relationship to meaning, but is it possible to connect grammars to semantic models consisting of meaningful notions, ontologies, taxonomies or other relational or contextual constructs. In our natural language this is done more or less unconsciously because language has usually been acquired together with meaning. For computer-based grammars this needs to be done explicitly. Notions need to be connected to objects or actions, sentences to activities, methods to pragmatics. This is the reason why even generative AI technologies like *Large Language Models (LLMs)* are not semantically structured by themselves. Generative AI systems just create more or less correct sentences or images in respect to grammars or other symbol structures, but are not able to explain what they represent.

There seems to be an upcoming technological path building semantic models combined with generative AI systems. This is not new to the “old AI methods” in the area of *Knowledge-Based Systems (KBS)* and *Expert Systems (XPS)* as well as *Natural Language Processing (NLP)* or *Conversational AI*. However connecting structure to sense will not be a brute-force automatic process like so-called *"Machine Learning"* or similar current approaches. We should never forget that when it comes to AI for education we will always need a connection to sense-making that bridges the gap from information, syntax and probability to knowledge, meaning and what we call truth and facts.

4.4 Intention-Based Computing

Even semantic computer models are not human-like activity systems by themselves. The represent and generate not necessarily in a useful and contextualized way. The human ability to have intentions, act and explain in context would be another next step to computers that understand or support human goals and behavior. In learning situations this might result in the *Intelligent Digital Assistant* guiding the learner through a curriculum or through a problem solving process. This seems to be basically possible, but is not necessarily emergent even from KBS.

To bring these computer capabilities together it needs an interactive computing archtecture that goes beyond calculus, text- and speech processing, and even beyond semantic modelling. Currently it is the teacher, who is capable creating and managing such contexts typically within the limiting classroom. What is needed are environments that allow teachers, students and more or less intelligent *Knowledge Media Machines (KMM)* [13] to connect into a creative environment to perceive, simulate, explain and document a structured mixed world of reality and virtuality. If such an environment relates to the accepted knowledge about our world, i.e. it is authentic, we would reach a kind of post-constructivist *Digital Knowledge Building Environment,* where the roles of teachers, students and technologies are fused into a creative blend of existing and new knowledge relevant for the learners.

To go one step further, the role of the guiding and leading teacher can be at least partially taken by computer systems as well, if they use semantic objects, scripts and activity models. They may guide the learner through a process of meaningful or even creative construction or deconstruction of the relevant world of the learners. However, as discussed above, intentions are not the same as plans or activity structures, there has to be a "big picture", like a curriculum or a problem at hand to start and lead the learners through an increasingly complex and demanding understanding and problem-solving path. So far this is provided by good teachers, not by machines.

5 A PROTOTYPE: AMBIENT LEARNING SPACES

In the research project *Ambient Learning Spaces (ALS)* we developed a flexible knowledge-building environment that has been studied in the field of schools and museums for several years ([14]-[17]). The basic architecture incorporated a set of interactive devices connected to a *Knowledge Media Repository* used by any number and type of teaching and learning modules (Fig. 1) [18].

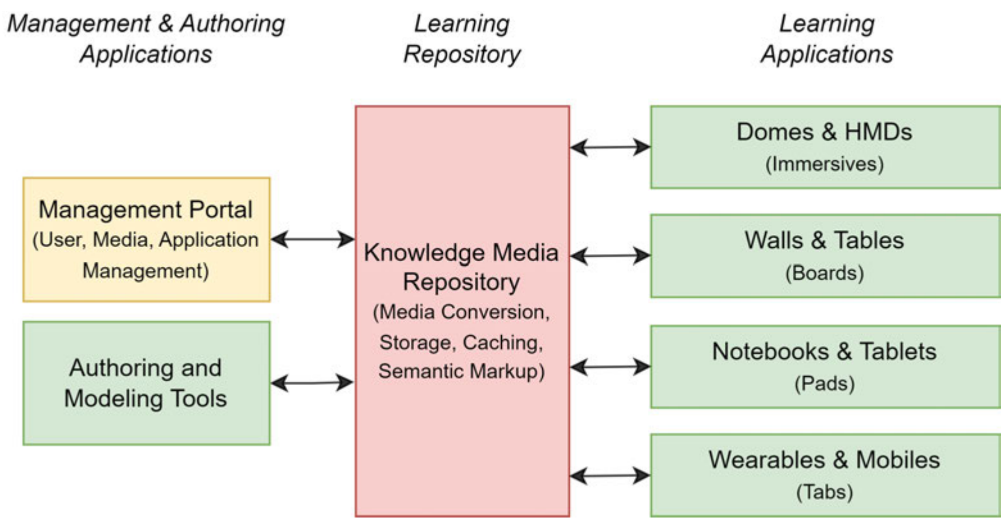

Figure 1: Basic Architecture of ALS

ALS consists of a set of application modules for teaching and learning that have been used and evaluated for many years to show whether they are useful for teaching and learning and how they have to be constructed as human-centered interactive computer technologies using *Knowledge Media* ([13],

[19], [20]). The above discussed different layers of technology support can be found in different modules of the ALS platform.

The perceptual support in ALS results from visualization modules for digital media up to 3D modelling ([21], [22]) for *Augmented and Virtual Reality* as well as *Interactive Domes* (Fig. 2).

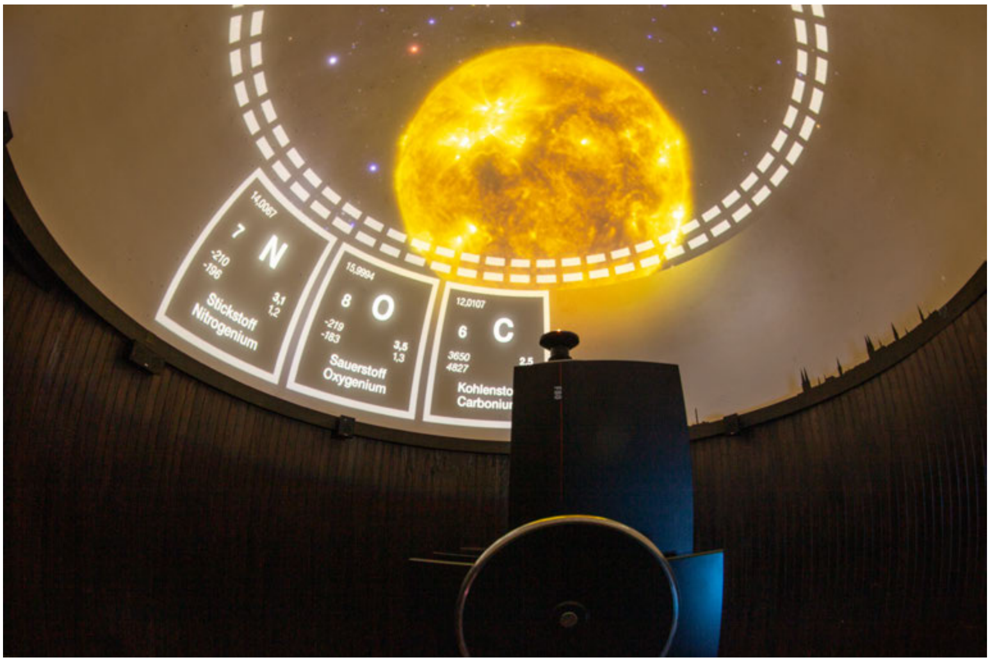

Figure 2: The ALS Interactive Dome ("Sternkammer" of the Grund- und Gemeinschaftsschule St. Jürgen in Lübeck,Germany © photo courtesy of Ralph Heinsohn)

The structural part in ALS comes through associate media to build *Hypermedia* structures out of any other media. The important semantic modeling has been enabled through *Semantic Tagging* in the *MediaGallery* (Fig. 3) ([23], [24]), the *SemCor* module for visualized *Semantic Networks* (Fig. 4) and *TimeLines* for chronological correlations (Fig. 5). A first step into intention-based computing for learning has been implemented by using a game- and task-oriented mobile subsystem *MoLES (Mobile Learning Exploration System)* ([25], [26]).

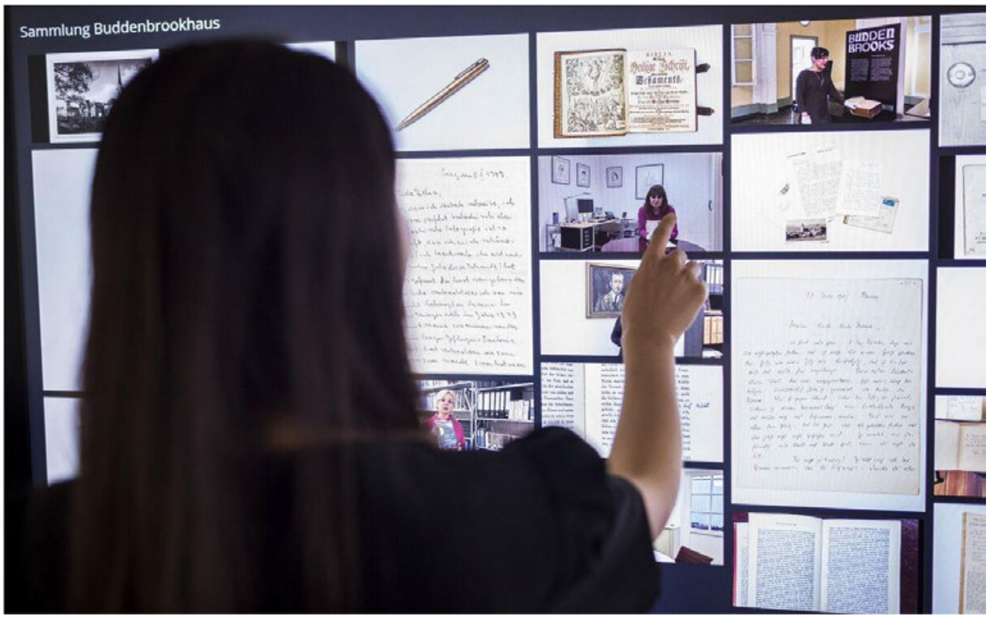

Figure 3: An ALS Semantic MediaGallery in a Museum
(Buddenbrookhaus, Heinrich-und-Thomas-Mann-Zentrum, Lübeck, Germany)

Figure 4: An ALS Semantic Network
(Buddenbrookhaus, Heinrich-und-Thomas-Mann-Zentrum, Lübeck, Germany)

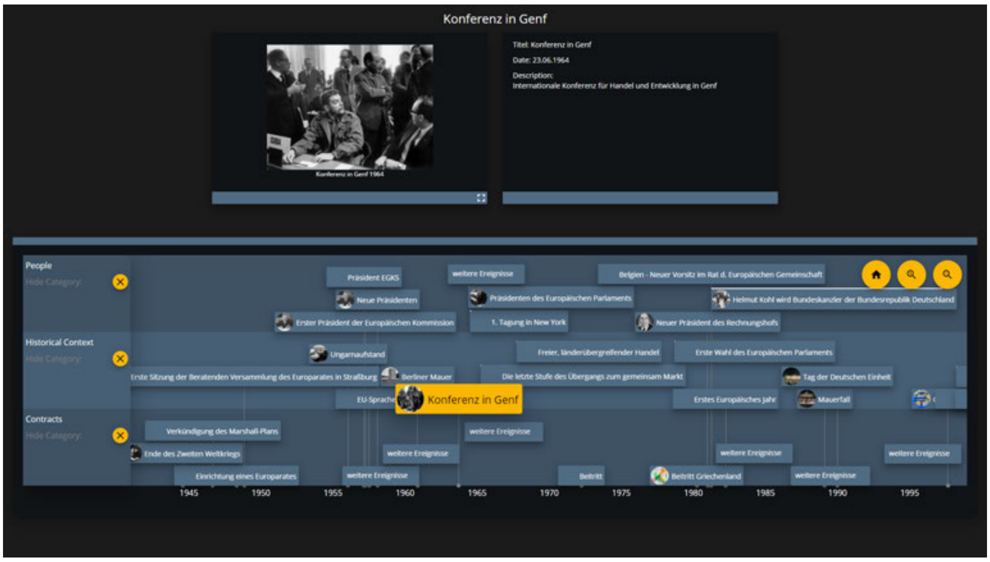

Figure 5: An ALS Semantic Chronology (Hanseatic School of Business, Economics and Administration Lübeck developed in a distributed project during the COVID-19 pandemic)

ALS has been used in several educational contexts. The main contexts have been schools, museums and the homes of the teachers and students (Fig. 6). As it is important for teaching and learning authentic knowledge to be in real contexts. Therefore additial contexts directly connected to the standard educational contexts like schools and museums have been biotopes, urbans spaces and corporate environments.

During the project through about 15 years, it showed that ALS came close to what we discussed above as a *Digital Knowledge Building Environment* with always bringing new challenges to incorporate new forms of human activities during teaching and learning processes. We concluded that such environments needs to be open to incorporate new methods of teaching, learning and machine intelligence ([27]-[29]).

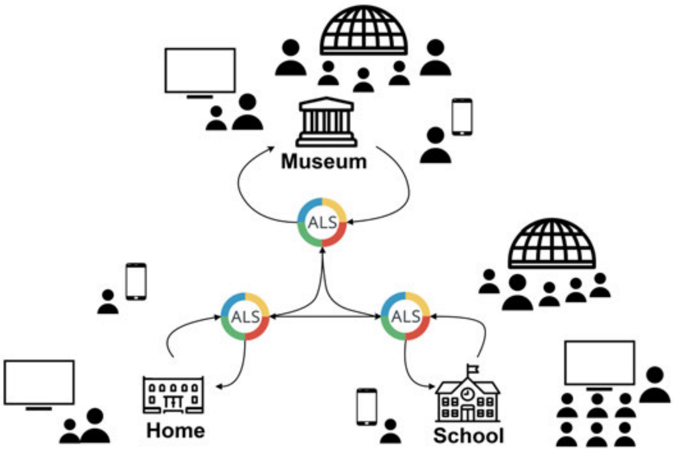

Figure 6: Connected Contexts of ALS

6 SUMMARY AND CONCLUSIONS

Education has often been a driving force for the development and use of technologies, especially information technologies. The gap between goals, ideas and solutions developed has always been deep and wide. In the area of educational technologies we need to be more aware of how to distinguish empty promises from promising opportunities. Examples of critical promises were the replacement of teachers by computers in the early 60s of the last century, as well as to believe in current generative AI systems as intelligent advisors and knowledge generators today. It seems much more promising to use them together with other methods to set up *Digital Knowledge Building Environments* for teaching and learning. As a next step, we may need semantic computer models combined with generative systems to enable learners to construct new knowledge from existing knowledge or to deconstruct answers to distinguish facts from fakes and insights from illusions.

ACKNOWLEDGEMENTS

We developed and evaluated the ALS system in the research projects "Ambient Learning Spaces" funded 2007–2021 by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) with projects no. 59778706 and 274995005. We also thank our school and museum project partners for their support and permission to do our field research in and together with their institutions.

REFERENCES

[1] G.G. Luce, "Can Machines Replace Teachers?," *The Saturday Evening Post,* Sept. 24, pp. 36–37, 102–106, 1960.

[2] E.G. Kerr, "Business and industry in the 70s find computer-aided instruction a practical answer to training problems," In *Proc. of the Natl. Computer Conference*, pp. 929–932, 1974.

[3] A. Kay, "Computers, Networks and Education," *Sc. American,* no. 9, pp. 138–148, 1991.

[4] M. Weiser, "The Computer for the Twenty-First Century," *Sc. American*, no. 9, pp. 94–104, 1991.

[5] V. Bush, "As we may think," *Atlantic Monthly,* July,1945.

[6] G. Marcus, "Hoping for the Best as AI Evolves," *Communications of the ACM,* vol. 66, no. 4, pp. 6–7, 2023.

[7] X. Zhan, Y. Xu, and S. Sarkadi, "Deceptive AI Ecosystems: The Case of ChatGPT," in *Proc. of the 5th Intl. Conference on Conversational User Interfaces (CUI).* New York: ACM, pp. 1–6, 2023.

[8] J. Baudrillard, *The System of Objects,* London, New York: Verso Books, 1996.

[9] J. Baudrillard, *Simulacra and Simulation,* Ann Arbor, MI: University of Michigan Press, 1981.

[10] M. Herczeg and M. Stein, "Human Aspects of Information Ergonomics," in M. Stein and P. Sandl (Eds.) *Information Ergonomics: A Theoretical Approach and Practical Experience in Transportation.* Berlin: Springer, pp. 59–98, 2012.

[11] M. Herczeg, “Mixed Reality Learning,” in N.M. Seel (Ed.), *Encyclopedia of the Sciences of Learning.* Boston, MA: Springer, pp. 2284–2287, 2012.

[12] M. Herczeg, “The Smart, the Intelligent and the Wise: Roles and Values of Interactive Technologies,” in *Proc. of the First Intl. Conf. on Intelligent Interactive Technologies and Multimedia (IITM 2010),* ACM, pp. 17–26, 2010.

[13] M. Herczeg, “Ambient Learning Spaces: The Role of Distributed Knowledge Media Management Systems for Computer-Supported Teaching and Learning,” in *Proc. of INTED 2023,* IATED, pp. 820–830, 2023.

[14] T. Winkler, F. Scharf, C. Hahn, and M. Herczeg, “Ambient Learning Spaces,” in A. Méndez-Vilas (Ed.), *Education in a Technological World: Communicating Current and Emerging Research and Technological Efforts.* Badajoz, Spain: Formatex Research Center, pp. 56–67, 2011.

[15] M. Herczeg, T. Winkler, and A. Ohlei, “Ambient Learning Spaces for School Education,” in *Proc. of iCERi 2019,* IATED, pp. 5116–5125, 2019.

[16] M. Herczeg, A. Ohlei, T. Schumacher, and T. Winkler, “Ambient Learning Spaces: Systemic Learning in Physical-Digital Interactive Spaces,” in *Algorithmic and Aesthetic Literacy: Emerging Transdisciplinary Explorations for the Digital Age.* Leverkusen: B. Budrich, pp. 97–115, 2021.

[17] M. Herczeg, A. Ohlei, and T. Schumacher, “Ambient Learning Spaces: A Connecting Link between Digital Technologies and Computer-Supported Pedagogy,” in *Proc. of INTED 2021,* IATED, pp. 6011–6021, 2021.

[18] M. Herczeg, “*Ambient Learning Spaces (ALS) – Interactive Learning Environments and Knowledge Media Machines for Post-Constructivist Teaching and Learning in the 21st Century,”* Technical Report TR-ALS-01-2024, IMIS, University of Luebeck, Germany, pp. 1–31, 2024.

[19] F. de Matros Müller and M.V. de Souza, “The Role of Knowledge Media in Network Education,” in *Intl. Journal for Innovation Education and Research,* vol. 8, no. 7, pp. 76–93, 2020.

[20] M. Eibl, H. Reiterer, P.F. Stephan, and F. Thissen (Eds.), *Knowledge Media Design.* München, Wien: Oldenbourg, 2005.

[21] D. Bouck-Standen, A. Ohlei, S. Höffler, V. Daibert, T. Winkler, and M. Herczeg, “Reconstruction and Web-based Editing of 3D Objects from Photo and Video Footage for Ambient Learning Spaces,” *Intl. Journal on Advances in Intelligent Systems,* vol. 11, no. 1/2, pp. 91–104, 2018.

[22] D. Bouck-Standen, A. Ohlei, V. Daibert, T. Winkler, and M. Herczeg, “NEMO Converter 3D: reconstruction of 3D objects from photo and video footage for ambient learning spaces,” in *Proc. of AMBIENT 2017, The Seventh Intl. Conf. on Ambient Computing, Applications, Services and Technologies,* IARIA, pp. 6–12, 2017.

[23] M. Herczeg, T. Schumacher, and A. Ohlei, “Ambient Learning Spaces: Discover, Explore and Understand Semantic Correlations,” in *Proc. of iCERi 2020,* IATED, pp. 7990–7999, 2020.

[24] M. Herczeg, “Ambient Learning Spaces: Chances and Challenges of Interactive Knowledge Media Platforms for Schools and Museums,” in *Proc. of iCERi 2022,* IATED, pp. 2378–2388, 2022.

[25] M. Herczeg, A. Ohlei, and T. Schumacher, “Ambient Learning Spaces: BYOD, Explore and Solve in Physical Contexts,” in *Proc. of iCERi 2020,* IATED, pp. 7979–7989, 2020.

[26] T. Winkler and M. Herczeg, “The Mobile Learning Exploration System (MoLES) in Semantically Modeled Ambient Learning Spaces,” in *Proc. of the 12th Intl. Conf. on Interaction Design and Children (IDC ’13),* ACM, pp. 348–351, 2013.

[27] M. Herczeg, “Ambient Learning Environments – Multimodal Interactive Teaching and Learning Environments with Low Threshold, Wide Walls, and High Ceiling,” in *Proc. of iCERi 2023,* IATED, pp. 8250–8260, 2023.

[28] M. Herczeg, “Education in the Digital Age: A Driving Force or a Lost Place,” *i-com, Journal of Interactive Media,* 20(3), Berlin, Boston: de Gruyter, pp. 263–277, 2021.

[29] M. Herczeg, “The Role of Digital Technologies and Human-Computer Interaction for the Future of Education," *i-com, Journal of Interactive Media,* 23(2), Berlin, Boston: de Gruyter, pp. 1–9, 2024.