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Sustainable Digital Environments: What Major Challenges Is Humankind Facing?

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Abstract: This paper identifies and discusses the benefits, threats, and vulnerabilities related to the digital revolution. It aims to motivate research and its funding regarding digital threats and vulnerabilities related, in particular, to anticipating unintended, undesirable rebound effects, tipping points, critically fast evolutionary change rates, trade-offs, etc. A brief analysis of the history of the mind and technology reveals slow technological development over tens of thousands of years (including the invention of a place-value digital number system). Then, a small series of groundbreaking ideas (e.g., binary logic, Shannon's symbolic analysis of relay and switching circuits, architectures of computing) enabled the industry-driven invention of programmable computing machines. Ultimately, the mastery of electron and semiconductor physics allowed for economical and seemingly unlimited storage capacity that made digital tools available to all domains of society. Based on the historical analysis, a coupled human-environment systems perspective (that includes a hierarchy assumption ranging from the human cell to the human species) enables the identification of several potential challenges to society and science. First, digital nano-engineering promotes genetic modifications (i.e., directed evolution), and synthetic biology enables a new level of the appropriation of nature. The understanding of cell-based biocomputers may call for new forms of logic. These and other challenges require thorough sustainability research in order to anticipate major changes on all levels of human systems. Second, the human individual is exposed to new forms of vulnerability. In particular, the potential epigenetic effects resulting from the excessive use of digital information of historically unknown speed, density, and contents and the loss of (the Western common-law right to) privacy resulting from big data (whose ownership is often unknown) should become subjects of research. Third, digital technologies are responsible for rapid changes in all social and economic structures. The paper suggests that thorough, discipline-based interdisciplinary research is needed in order to develop basic knowledge for creating and managing resilient relationships between human systems and their digital environments.

Keywords: digital revolution; digital threats; rebound effects; genetically modified organisms (GMO); cell-based computers; cell-based computing; environmental epigenetics; loss of privacy; appropriation of nature

1. Why Do Digital Environments Call for Special Attention?

1.1. The Social Dimension of the Digital Revolution Is Not Yet Well Understood

The development of Homo sapiens and human societies is characterized by a couple of fundamental transitions. The present paper starts from the proposition that, phylogenetically and historically, many impacts linked to the emergence of digital environments (E_D) have the same gravity as the mastery of fire, the development of speech, the invention of agrotechnology, and the Industrial Revolution [1]. We also propose that certain applications of digital technology, particularly in synthetic biology, herald a new stage of human evolution. One of the goals of this paper is to identify essential threats on human systems that have—directly or as potentially higher ordered—rebound effects on physiological or social layers of human systems. As we argue in the conclusions, these threats demand large-scale research programs directed at a better understanding of what these threats look like and how they may be properly managed.

In this paper, E_D includes all human-made, computer-enabled, stored, processed, retrieved, and transmitted digital data. These range from the hardware and software related to technical devices such as heart pacemakers and autopilots for cars and planes to new media that coordinate all domains of the individual's life including virtual life-spaces to electronic markets and electronic money, and global stock markets as well as real-time-processing social media that provide Internet-based, user-generated content. To better understand these types of impacts of the digital revolution, let us look first at several impacts of E_D on human systems within the range of the human individual to the human species.

On the level of the individual's interactions or group formation, computers and even robots have already become an interactive part of all the domains of personal everyday life [2]. Furthermore, there is evidence that human learning [3], thinking, and motor skills [4,5] are changing. The patterns of human interaction, communication, group formation, problem solving, negotiation, and conflict resolution are currently undergoing rapid changes. Already with the introduction of the Internet in companies, the direct personal contact with other people has decreased [6] and new forms of communication developed. Sometimes people turn away from the person next to them and use smartphones to communicate with others far away or for other purposes. There are empirical findings that reveal that personal relationships decrease and social anxiety increases with intense gaming and Internet use [7,8]. But we also have to acknowledge that those with social anxiety become more likely excessive online gamblers [9] and—on the other hand—that there is evidence that virtual gaming may induce lifelong friendships [10]. A vast share of direct contact is being substituted with communication via digital channels such as the Internet, Skype, Facebook, or newer social media. This calls for looking for new cues that are substitutes for the multiple signals transmitted in face-to-face communication. Thus E_D also allow for new ways of forming groups and interacting, and the building of a collective mind, allowing us to also see the positive side and the potential of the individual's forming of a collective mind [11].

From a sustainability perspective, we may question the positive and negative effects of these changes on the social structure and discourse culture. Are we becoming less accustomed to and capable of reading nonverbal signs of human interaction and other issues, such as building and communicating group norms? There is empirical evidence that children between the ages of 8 and 12 years—a highly sensitive phase for identity formation, the development of social networks, and relationship building with peers who may serve as models and support—are negatively affected socio-emotionally by certain types of media use. A comprehensive study conducted with girls showed that high levels of media multitasking induce feelings of being less successful and not being normal, and reduced hours of sleep [12].

Yet E_D enhance and augment human performance. We can identify opportunities for substituting, restoring, and augmenting normal physical- (i.e., energy-based), sensory- (sight, hearing, etc.), and cognitive- (memory, information retrieval, etc.) related human performance and interactions, as well as those related to conviviality (e.g., long-distance communication).

However, at the same time, interaction with the physical environment is reduced, as the digital screen does not provide subtle signals such as changing skin color or body odor under stress. Rapidly increasing amounts of time are spent with virtual realities that are presented via audio-video output channels. We are substituting direct, analog interaction for the three-dimensional world. We discuss in what ways this is relevant for child development and, specifically, for brain development. An interesting aspect is that computers and robots are becoming more and more human-like. Thus, from a psychological perspective, the boundaries between real life and a secondary life as an avatar [13] seem to becoming blurred, and some psychologists worry that individuals may be deluded into thinking that humanoid robots will replace pets, caregivers, or other human beings [14].

Business organizations are continuously facing the development of new digital products, and new types of market actors appear that change the structure of markets. Digital cameras have largely replaced analog cameras, and online shopping is replacing much of the purchasing done at physical "brick-and-mortar" locations. Companies emerging from the new media industry are entering the automotive market and challenging the historically developed cluster of automobile manufacturers, and a developing 24-h distributed electronic stock exchange with Internet multicast systems [15] is affecting the global stock market and its volatility and risks [16]. The digitalization of companies will heavily affect the companies' communication and leadership structures, the access to knowledge about the supply chain (i.e., the direct partners and competitors), but also trust building as direct communication will be reduced, just to mention few issues. And, E_D will open a new chapter in (adaptive) interactions between human systems and machines.

On the level of society, the pervasiveness of E_D also opens new options for designing economic, legal, educational, social, and political structures, including democracy digital structures worldwide affects social structures and organizations. According to major insights from anthropology [17], fundamental technological progress that affects the basic processes of societal reproduction, such as the digital revolution, will cause fundamental societal transformations characterized by new social and power structures [18] and new types and levels of human systems. We discuss in what ways the emergence of supranational systems and the emergence of a (global) mind-set of the social species become real by E_D. E_D are a major pillar for economic growth, better health care services, and improvements in numerous domains of life. However, they also create opportunities for new forms of criminal activity and societal disruption, e.g., cybercrime by ransomware attack [19,20] or terrorism in cyberspace [21]. E_D also open new options for designing economic, legal, educational, and political structures, including democracy.

However, in addition, we may postulate whether E_D are also generating new structures on the level of the human species. Here, we conceive of the domains of the world "generated by Information and Communication Technology (ICT)" [22]. A critical issue is whether the human species becomes a (collective, real-time operating) mind (in the way that global economics has developed a joint-regulating structure as a result of a global stock market). (see also [23–25]).

We argue that this brief (naturally incomplete) review on impacts on human systems in the range from the individual to the human species provides a mixed and ambiguous image. It is clear that these issues asks for research (which is partly ongoing) for a better understanding of the impacts of digital environments on human systems. But, we argue that for getting a comprehensive insight into the new quality of E_D, we have to take a look at the cellular level.

1.2. Computers Become More Than Tools: The Coupling of Cells and Digital Devices

Computers are more than tools as they represent a new type of active, machine-based agency [26]. This can be understood easily by reflecting upon different entities of the human environment. Let us think about your neighbor's refrigerator, your personal car and modern/motorized traffic facilities that you are using, or your gut flora. All are parts of your environment, although they have a different status. The type and brand of your neighbor's refrigerator is completely unimportant to me. This is fundamentally different from your gut flora; gut flora is essential, as no one can live outside his mother's womb without flora (i.e., please note that the embryo does not have gut flora before leaving the amnion). Human individuals and gut flora are inextricably coupled in the sense that one cannot live without the other. This is not the case if you think about deciding not to use your car or other traffic facilities. You would not die, but your life and your identity would fundamentally change. You can imagine a scenario where all people do so (as the lives of traditional Amish people may suggest).

The new quality of human–digital environment relationships by E_D becomes evident if we consider nanomachines such as the Benenson automata [27,28]. These automata are or will be able to diagnose and intervene in cell processes. Thus, E_D affect all seemingly inextricable interactions with all living systems, ranging from the cell to the human individual and from the individual to the human species. From a theory perspective, this calls for a conceptual structuring of the relationship of human systems to environmental systems. This is done in the following section.

1.3. Computers (E_D) Will Become a Mind: A Coupled-Systems Perspective

E_D are human made. Historically, their invention, development, use, and social impacts are genuinely dependent on different human systems (H), ranging from the human cell via the individual to the human species and the interests, needs, drivers, capabilities, and various resources these systems have. E_D are part of the human environment. In order to provide a definition of human systems that is conceptually consistent for all levels of human systems and for a better understanding of the interferences between hierarchy levels of human systems (see Section 4), it makes sense to base a concise definition on the smallest unit of a human, which is the zygote, i.e., the one-celled, fertilized human ovum that has been entered by a sperm. The human individual is defined as all living cells that emerged from the zygote and the interactions of these cells. The environment of a human system E is defined simply as the set of atoms of the universe minus the atoms of the individual's cell system [29]. This definition can be applied to all levels of human systems (see Figure 1a). For instance, if we consider a company (which is conceived of as being an organization) as a human system, then it can be defined as the activities of all the cells of the owners and employees that are (legally) assigned to the company.

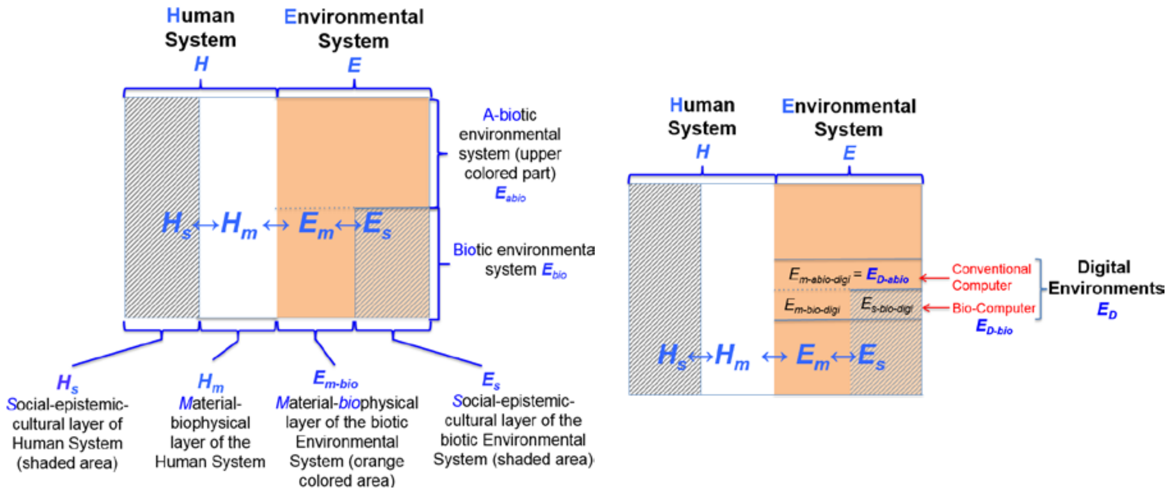

Figure 1. (**a**) The two complementarities of/in human and environmental systems, i.e., the "set-theoretic" complementarity between human and environmental systems, and the two layers of material-biophysical and the social-epistemic-cultural layer of human systems (such as the human cell, organ, individual, society; see [29]) and of the biotic environmental system. E_D are part of the environmental system E of human systems H; (**b**) Conventional computers are part of the abiotic environment; if cells are integrated into computers, computers get a "mind" (i.e., a socio-epistemic-cultural layer). All variables are defined in Box 1.

For this simple material, set-theoretic definition, it is most important that human systems H and environmental systems E are considered as inextricably coupled systems, such as the two sides of a coin or Yin and Yang in Chinese philosophy. On the side of human systems, we further postulate that we can distinguish between a material-biophysical layer H_m, i.e., the cellular system related to a human system, and the socio-epistemic-cultural layer Hs. This system view is presented in Figure 1. Hs is also called mind. On the level of the individual, the mind includes, among other elements, factual knowledge about the universe and procedural knowledge, i.e., the different types of analytical and intuitive heuristics that are available to process knowledge [30,31]. In addition, groups have a mind. The mind of a group consists of the group's norms and attitudes, the explicit and implicit behavioral and decision-making rules, shared and tabooed beliefs, customs, etc. that regulate the group's activities.

Box 1. List of abbreviations.

E	Environment (of a human system H) defined as the atoms of the universe minus the atoms constituting a specific human system H
$E_{m\text{–}abio} = E_{abio}$	Material, abiotic environment (the atoms belonging to the abiotic environment of a human system)
$E_{m-bio} = E_{m-bio-nondigi} \cup E_{m-bio-digi}$	Material, biotic environment (the atoms belonging to the biotic environment of a human system), the biotic environment is a union of the ("natural") non-digital biological and bio-computers (and other prospective hybrid, digital technology-based biotic entities)
E_{s-bio}	Social, epistemic, cultural layer of the biotic environment
$E_D = E_{D-bio} \cup E_{D-abio}$	The digital environment is a union of the (upcoming) biotic digital environment (i.e., biocomputers) and of the abiotic digital environment
$E_m = E_{m-abio-nondigi} \cup E_{m-abio-digi} \cup E_{m-bio-nondigi} \cup E_{m-bio-digi}$	Material environmental layer conceived of as the material composition of the material environment without computers, the (traditional) abiotic computers, the biotic environments without biocomputers, and biocomputers
E_s	Socio-epistemic-cultural layer of the environment of a human system
H	Human system (ranging from the cell, cell systems, organs via the human individual, group, organization, institutions, societies, supra-societal systems to the human species)
H_m	Material human system defined as the activities of cells of the (a) individual; or (b) of subsystems of an individual; or (c) the activities of members of a human system that are assigned to a human system H and of the interactions of these cells
H_s	The socio-epistemic-cultural layer of human systems H
HE_DS	The coupled human–digital environment system

The mind emerges from matter. Thus, the mind of a human system cannot be considered independently of the cellular layer, e.g., of an individual or the individuals who constitute the human system of a company. However, there is no one-to-one (isomorphic) relationship between knowledge and the configuration of the cells of a human. Thus, analogous to wave-particle duality [32], we postulate a body–mind layer complementarity for all living systems. The term layer here refers to the proposed system model, which we present in order to better understand sustainable E_D and how they are related to human systems. From a (realist) constructivist perspective [29], both layers are constructs to approach the nature of human systems.

Cells are supposed to have a mind and thus may be conceived of as cognitive systems and decision makers in the sense that they do not function as chemical reactions but become activated (i.e., fire or react) based on their memorized history and a set of complex environmental information [29]. This is a widely shared view [33,34] that has been elaborated, in particular, for the immune system [29,35–38].

We may further distinguish between a biotic environment that consists of the living cell-based systems E_{m-bio} (a minor part of the universe) and an abiotic environment E_{m-abio} (see the right-hand box in Figure 1a). If we consider a specific human system H', all other human systems (besides H') are part of the environment. According to the above definition, any biotic system, i.e., also prokaryotes such as plants and bacteria have a mind (see below).

Let us briefly take a closer look at the cellular level, as we are in a transition where cells become integrated into (abiotic) computers [39]. In addition, the view that nanocomputers may alarm or activate cells is of interest from a medical and, thus, a sustainability perspective. Cell-based beings do not behave like machines or chemical processes. The human cell system as well as the structures and functions of human cells are highly complex; the mechanisms in the adaptive and innate human immune system functions alone are fundamentally different. We also assume that learning in the human brain, which is based primarily on the interaction of networked cells of the brain with proteins (e.g., signal transmitters), naturally differs fundamentally from learning in plants or simpler organisms such as the simple model organism *Escherichia coli* (*E. coli*) bacteria. As the title "Solving a four-destination traveling salesman problem using *E. coli* cells as biocomputers" [40] reveals, these simple organisms are currently integrated in cell-processor-based computers [41].

We may further distinguish between a biotic environment that consists of the living cell-based systems E_{m-bio} (a minor part of the universe) and an abiotic environment E_{m-bio} (see the right-hand box in Figure 1a). If we consider a specific human system H', all other human systems (besides H') are part of the environment. According to the above definition, any biotic system has a mind. This is assumed to hold true (but presumably in a different, although still widely unknown, manner) for prokaryotes, which are organisms that lack a nucleus and other organelles, and eukaryotes, which are more-highly developed organisms that possess a nucleus. Bacteria are prokaryotes. Plants, animals, algae, and protozoa are eukaryotes.

However, plants are also thought to demonstrate intelligence [42–44]: "It is increasingly recognized that plants are highly sensitive organisms that perceive, assess, learn, remember, resolve problems, make decisions, and communicate with each other by actively acquiring information from their environment" [43]. The conceptual framework of plant intelligence refers to transcriptional imprints. If plants are exposed to threats (e.g., pathogens), certain proteins are produced by specialized cells [44], which then produce antigen-like molecules for defense and communication (by danger signal) with other plants. For example, some plants react if a predator appears or if a human has torn leaves from them [45].

The abiotic environment E_{m-abio} includes all non-living systems, in particular machines. If we exclude the (tiny section) of digital computers from this digital environment, this part of the environment can be denoted as $E_{m\text{–}abio\text{–}digi}$. All marketable computers up until now have been completely abiotic (although, presumably, micro-organisms may be found in the envelopes of most computers). Thus, current (marketable) computers are not assumed to have a mind; however, this is presumably changing if cells are being integrated into computers. Therefore, computers are becoming biocomputers, and accordingly, a scientific challenge is to anticipate how the rationale of these systems, which have a mind, differ from conventional computers in general and specifically.

Conventional computers may represent and process material, e.g., electronic states of storage disks, which may be considered analogs to factual knowledge (see above) by certain algorithms, but this is done mechanically (even when stochastic algorithms are involved and program structure changes depending on environmental information). Intelligent humanoid computers and robots have been fictional in the past, but this may change if we consider biocomputers in which cells take on essential functions. This is represented in Figure 1 when introducing a mind $E_{S\text{–}digi}$ (i.e., an epistemic layer) to biocomputers. What this may mean from a sustainable-development perspective is discussed below.

The transformation from computers to biocomputers certainly has greater significance for humankind than the switch from analog to digital media. Biocomputers represent a type of hybrid machinery, such as a horse-drawn carriage. Evolutionarily, to produce that conveyance, the wheel had to be invented, the horse had to be domesticated, and the yoke and harness had to be developed. These inventions and developments have different depths and different backgrounds that were not a matter of course, as may be seen from the history of the high culture of the Maya, who did not use the wheel [46]. However, biocomputers may bring about new types of imponderabilities and vulnerabilities, as biotic systems do not work mechanically, and how they react depends on their biography.

From an evolutionary perspective, the most fundamental transformations are the manipulation of the genetic code and the intervention in cell processes. These affect natural variation (besides natural selection and the evolution of a changing population resulting from transmission to future generations), the most important mechanism of adaptive evolution. Human adaptive evolution has accelerated in the last 40 years, and traditional patterns of evolution may have undergone alterations in recent times as a result of birth control and other factors.

1.4. The Vulnerability of Coupled Human–Digital Environment Systems (HE_DS) Should Be Understood

A critical question is under what constraints the individual and societies of the future become vulnerable because the interactions among humans become degraded and shaped by virtual second-life experience that fails to meet the needs of viable human systems. This may require that societal models such as democracy be adapted or renewed [47], but this is the negative side of the coin. Similarly, we may ask under what constraints virtual experience may be seen as an essential enrichment of the individual's development, in the sense that new qualities of experience emerge that, in turn, allow for advanced and perhaps augmented forms of cognition and behavior, marking a forward step in evolution that may be promoted by an innovative type of technological embodiment [48]. However, there is also the question of how the functioning and organization of society is changed by E_D. We may question whether and under what constraints (the ideal type of) democracy is promoted [49] as cyber-utopians expect [50] or whether authoritarian governments are strengthened by the freedom of the Internet [51]. On a global level, we may question whether the human species becomes a real-time mind and collective rationality develops a new quality. In this place, we want to stress only that the impacts of the different levels of human systems (here individual, society, and human species) are interrelated. We may take the "social digital divide" [52] as an example. If a large share of society is not participating in social discussions because their Internet use is restricted to commercial and individualized use, the idea of e-democracy will fail [49]. This suggests that any sustainability assessment of HE_DS should be of a multilevel type, for instance, when analyzing how impacts on the individual are related to changes on the level of the society.

The simplicity of digital systems is notable. Digital computers work with a few basic, discrete signals, mostly of a binary type, that can be conceived as discontinuous waveforms with a finite range of levels [53]. By contrast, analog information technologies work with signals that show infinite, continuous states. Let us consider a protein, which may be considered the workhorse of cell communication. Proteins are large, three-dimensional biomolecules that are built by different amino acids. How the protein folds in compact formation and what the shape (i.e., the location of all atoms and its elementary particles of the molecule in the three-dimensional space) of this complex molecule looks like depends on the history of environmental information [54,55]. This leads us to complexity theory. There is no doubt that the complexity of analog structures is much higher than that of digital real world environments. If we want to describe the three-dimensional dynamics of the atoms of a complex molecule, chess—as human-made digital environment—may serve as a benchmark of comparison. The chessboard has 64 squares with 32 pieces. The number of chess games amounts to 10^{128}. This is much larger than the atoms of the universe, which amount to 10^{80} [56]. If the locations of the molecules' atoms would matter for understanding the (analog) process related to (inner-)cellular information transition, it seems evident that describing the dynamics of a single protein would overburden digital computing and other forms of description would be necessary. The digital-analog disparity may be well portrayed by the saying: You can exactly copy the most complex digital data one by one but not the simplest atom.

There are many ways to identify the date of the beginning of the digital age. One way is to identify the year in which the majority of unidirectional and bidirectional telecommunication became digital. This was in 1999 [57]. The majority of all stored produced data has also been digitally stored since 2002. Thus, we can denote the turn of the millennium as the start of the digital age (see Figure 2).

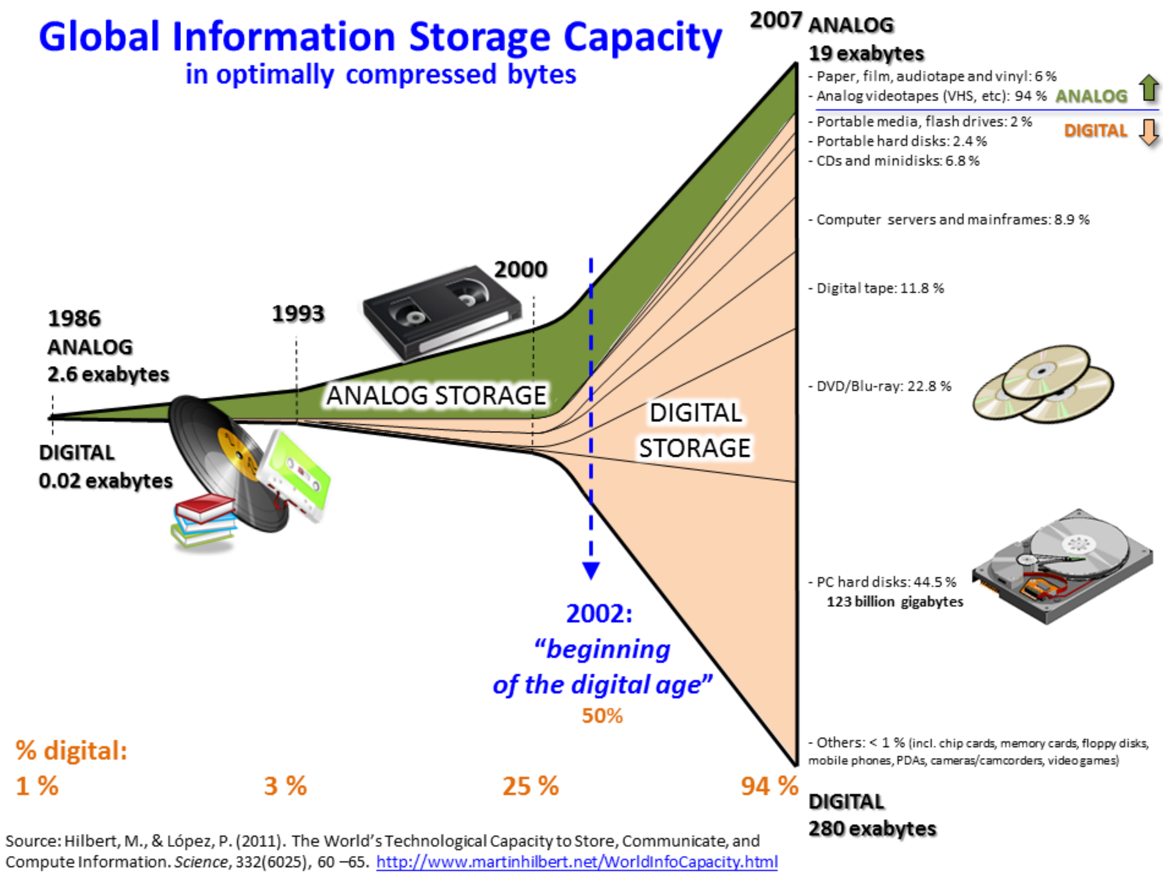

Figure 2. The development of cheap storage capacity [57,58] is seen as the key to the start of the digital age (see also [59]).

Information and the computation of information from networked digital data computers are ubiquitously devouring all domains of the human life cycle. These include storing DNA data, phone calls, records of financial transactions, and more, i.e., potentially any action someone undertakes. Thus, we have to become concerned about how to organize our digital funerals, as our entire lives, from birth to death, will be digitally recorded. Cheap microprocessors allow for pervasive interaction with products, buildings, and other people and subjects of interest.

We argue that the understanding of the ontology of E_D is a main prerequisite for understanding the hidden, delayed, and unintended impacts of the digital revolution on the socio-epistemic-cultural layer of different levels of human systems. A White House report elaborates that big data have a huge potential for social and economic development, but they include many threats for the individual and certain groups (e.g., when searching jobs or purchasing homes). Personal data are available in an uncontrolled manner [60]. From a societal perspective, the interpretation of patterns in (mostly noisy) big data calls for new types of inference and validation [61]. We are facing correlations on an abstract level with a mostly unknown genesis. These data require new rationales of selection and interpretation. It is doubtful whether meaningful strategies and methodologies for interpreting patterns of data are already properly available today.

1.5. Do Social Systems Show Sufficient Adaptive Capacity to Cope with the Rebound Effects of this Rapid Transition to a Digital Environment?

Almost any significant technological development is Janus-faced. This holds true for the stone-aged ax, the steam engine, or the mastery of nuclear power as well as for E_D. The technological innovation of fossil-fuel-powered machines allowed for heavy and fast transportation that improved agricultural efficiency and the capacity to nourish people, among many other benefits. But at the same time, there have been environmental and social costs, including ecological damage and the poverty of the working class. Looking back, the impacts of the costs of opportunities in unintended feedback loops resulting from the use of industrial resources have been underestimated. Although the loss of ecosystem services by forest famine [62], climate change (already described on a local level by [63], and air pollution (e.g., London's smog) were all noticed early in the 19th century, it took until the close of the 20th century before these threats were properly acknowledged. The factor that was missed for so long was that insufficient attention was paid to what Herbert Spencer [64] called the total environment, i.e., the environmental setting that allows for life. This changed with the concept of sustainability, which integrated social, economic, and environmental factors. In this text, we conceive of sustainable development as an ongoing inquiry on system-limit management (i.e., on avoiding unintended system collapses) in the frame of intra- and intergenerational justice [65,66].

A critical question is whether humankind, with respect to E_D, is facing a similarly delayed awareness regarding the impacts on the natural environment and the potential critical rebound effects on human systems as it has been with the anthropogenic pollution of terrestrial, aquatic, and atmospheric systems. E_D have strong positive potential and "can be seen as a new grid of control on the planet" [67]. However, given the tremendous impacts of the spread of this technology, it is changing societal structures in a fundamental manner. If we acknowledge the rapid speed of spread, we must, in particular, question whether we are overburdening the adaptive capacity of human systems necessary for establishing the resilience of coupled human–digital environment systems HE_DS [68].

The intense use of E_D also affects our bodies (i.e., H_m of an individual). On a general level, we can state that the amount, intensity, and distribution of information for the perceptual channels of sight (visual), hearing (auditory), touch (tactile), smell (olfactory), and taste (gustation) will change. Humans will increasingly process computer-mediated, simulated or virtual, potentially artificial, highly elaborated, and highly stimulating information. This implies that the perceived experienced physical and virtual environments are subjectively merging and is referred to as immersion. The intense interaction with a virtual world leads to embodiment [69] and multiple physiological reactions. Extensive interaction with E_D may cause cybersickness, which sometimes resembles motion sickness (when we perceive incongruent sensory inputs [70]); but can be differentiated and also appears independently from visual perception [71,72]. Similarly, the health impacts of excessive Internet gaming are known [73]. Addiction-related Internet behavior has become a significant issue [74,75] affecting all kinds of communication including sexual behavior [76].

This paper pays special attention to the resilience of inextricably coupled human–digital environment systems HE_DS. Resilient coupled HE_DS show sufficient adaptive capacity to cope with uncertain tangible impacts that result from uncertain threats. Resilience is complementary to vulnerability and seen as an extension of the risk concept [68]. Thus, vulnerability is defined as a function of exposure to a threat, sensitivity with respect to impacts of threats, and the adaptive capacity to cope with these impacts. Resilience and hence vulnerability management is seen as an important aspect of sustainability management.

The difficulties of adaptation to new E_D may be well illustrated by turning the global economy into a digital economy. Digitalized products and services can be produced in all places. Market leaders are multinational companies that look intelligently for options to save taxes by suitable transnational inner-company transactions. This has become possible as intangible operations and assets became more important (and often more valuable) than physical transactions. The costs of storing and transporting digital products are almost zero. Digital products can be replicated at almost no costs, and many firms "outsource many corporate functions to territories with lower costs" [77] (p. 15) if tangible products do not allow for smart solutions. We should also not exclude the possibility that the ownership of cloud technology, 3D printing, and the Internet of things (IoT) may disappear among the boundaries of the 193 countries of the United Nations. A critical question is what the tax system of a digital time might look like. Some countries and states of U.S., for instance, try to rely on given general laws to govern the taxation of digital goods. Others, such as Kentucky, have enacted new laws that specifically address taxation of digital goods [78]. As it is difficult to reliably tax such products, one idea would be to shift all taxation to the consumer and thus to introduce new mechanisms. Digital economics demonstrates a new type of mobility. The national taxation laws are inhomogeneous and certain mini states may offer special opportunities. Thus, one may ask for a new global taxation in a kind of supranational setting, as exemplarily demonstrated by the European Union for environmental regulations and other issues (but not yet for taxation).

1.6. The Structure of the Following Sections

The previous sections have provided a blueprint for describing several fundamental challenges of E_D from a coupled human–environment systems perspective. But how and when did the development of E_D took place? What is the ontology of E_D? What are key inventions of E_D? And how may critical vulnerabilities emerge? Section 2 takes a history of mind perspective, but also reviews some salient characteristics of the brain, which may be viewed as the hardware of the mind [79,80]. Section 3 deals with the history of digital technology. The subsequent sections present summaries of the development of the brain, mind and of (physical) technologies chapters. A detailed description can be found in the supplementary information. The discussion includes five propositions on fundamental challenges of HE_DS.

2. What Episodes from the History of the Human Mind H_m Enabled Digital Environments?

We look at the triad brain (as a biological organ H_m, here m stands for material-biophysical, see Box 1), mind H_s (s for social-cultural epistemic), and digital technology from the conceptual framework presented in Figure 1. Technology may have different meanings. In the following, technology is seen exclusively seen physical products and thus as part of the environment E. This is mentioned as sometimes it is considered as knowledge and occasionally as the operative physical capabilities. E_D include abiotic conventional computers E_{D-abio} and biocomputers E_{bio} if (parts of) living cells are integrated into computers (see Figure 1b).

2.1. The Brain Is Phylogenetically Changing Slowly, but Cultural-Environmental Impacts Are More Greatly Affecting the Individual's Brain Structure

The human species has neither the largest absolute brain size (although it is the largest relative to body weight among large mammals; [81]) nor the longest DNA. The size of the human brain increased over a long time, before it decreased by the size of a tennis ball (linked partly to a reduction in body weight, see Table 1), particularly in the case of sedentism, which asked for different sesomotoric skills [82,83]. This may align with the phenomenon of domesticated animals having approximately 15%–20% less brain weight than their wild ancestors [84–86].

Table 1. Brain development.

Time Scale (Thousands of Years Ago)	Brain Size (cm^3)
3,000,000	500
100,000	1500
10,000	1500
today	1300

The development of technologies emerged remarkably slowly [87,88] for a long time and then accelerated at an amazing pace. The first stone tools date from two to four million years ago. The first bone and antler artifacts date back only approximately 90,000 years, but they began to spread just about 40,000 years ago, the period when art, language, religion, and a first cultural explosion took place [85].

The speed of technological development reached a new level with the beginning of agriculture some 10,000 years ago. However, from the first mechanical computer in the mid 17th century, it has taken only a short period for the whole world to be networked with electronic computers. This represents an obvious flexibility related to culturally created environments.

However, there are also interesting ontogenetic brain changes. For instance, the brains of London taxi drivers, who are required to have an exceptionally detailed, large-scale training of the cognitive map for licensing, develop a larger hippocampus [89,90]. This suggests that small children's encounters with complex 3D digital game worlds may certainly have the same intensity and ask for different sensomotoric skills than the games of children some decades ago. Whether and in what ways the rules of evolutionary selection and epigenetic effects play a role in a digital society is currently unclear and may call for investigation. There are some neurocognitive–archeological [91] and experimental neuropsychological studies that suggest the brain "is a cultural artifact" [92] and not an autonomous machine primarily determined by internal factors [93].

Historically, the view of the brain as plastic and environmentally contextualized [94] it supported by the phenomenon that we can find periods and regions of vivid intellectual and social development in Europe such as the antiquity (ca. 500 BCE until 300) and the era beginning with the Renaissance. Contrary, during the medieval period (also called the Dark Ages), much knowledge was lost. The new domain of cultural neuroscience provides insight into the plasticity of the brain [95–97]. People have adaptive capabilities that enable them to survive in the Sahara, in the Arctic, in tropical forests, in space shuttles and space stations, and in submarines. In addition, the human today has a significantly smaller genetic variation worldwide than chimpanzee populations that are separated by a few kilometers [98,99]. The cultural formation of the brain is an essential factor for utilizing the creative potential of the brain. The brain will be formed by cyberculture. How this looks like should become a matter of research.

2.2. What Is Gained and What Is Lost by the Cascade of Abstractions Forming the Digital Environment E_D?

From a cognitive and epistemological perspective, the emergence of ED is linked to a set of different levels of abstractions [100–102]. Table 2 presents some groundbreaking ideas. The denomination of numbers (which goes beyond tally lists) goes back just 6000 years. However, in cases such as the Roman numerals, the numbers did not function for calculation. This called for the invention of zero and of place value numbers some 3500 years later [103]. Zero formed the bridge from counting and calculation, and can be considered the greatest single abstraction of the human species. All place value or positional numbers N can be written (as a specific polynom) in the form of $N = \sum_{k=0}^{l} n_k m^{l-\mathrm{k}}$ with $n_k \in \{0, 1, \ldots, m\}$, where k is the positioning index and m is the base. For instance, with this base 10, 432 may read:

$$4 \times 10^2 + 3 \times 10^1 + 1 \times 10^0 \tag{1}$$

There had been number systems with many different bases (e.g., 60 of the Babylonians about 5500 years ago, which still show up in time measurement).

The idea of mechanizing computation dates at least to 1632 and Wilhelm Schickard (1592–1635), and got an update in 1822. For running calculations automatically, British mathematician Charles Babbage (1792–1872) applied the idea of Joseph-Marie Jacquard's (1752–1834) punched-card programming of weaving machines to computers which is similar "stored computer programs in von Neumann architecture" [100].

At that time the road to general abstraction and to the maximum reduction to the binary-number system was paved by giants of thought such as Francis Bacon (1561–1626), Blaise Pascal (1623–1662), and Gottfried Wilhelm Leibniz (1646–1716). The next step, i.e., a comprehensive mathematical analysis of symbolic, binary logic was elaborated by Boole (1815–1864) [104,105] and refined by Charles Pierce (1839–1914).

Multiplication tables with $a, b \in \{0, 1\}$ include only four cells and are well suited for electromechanical relays. This was utilized by Claude Shannon his bridge-building PhD thesis from logic to computers: "A symbolic analysis of relays and switching circuits" [106]. Many inventions on architectures of computers were pushed in the WWII such as Turing's theory of computation [107] and von Neumann's architecture can be seen as primary theoretical milestones of the development of computers before the late 20th century. There are many inventions related to the computer. Table 2 (third row from the bottom) presents the idea of utilizing energy of electrons from rays (i.e., an analog technology) for constructing a rewritable memory (i.e., the Williams tube) and the development of a computer language [108]. Naturally there are other ideas such as artificial intelligence (AI) [109,110] or parallel computing. However, I think that they are not really linked to similar fundamental stages of abstraction as presented in Table 2.

Table 2. Some stages of mind development for digital computing.

Time Scale (Thousands of Years Ago)	Type of Abstraction	Core Idea	References
6000	Invention of numbers	Measuring magnitude by numbers of pieces	Wußing [111]
2600	Invention of "0" and place value numbers	Place value numbers for numerical calculation	Ifrah [101]
500	Binary numbers	A maximum simplified number system for calculation	Kaplan [103]
393	Mechanization of computing	The idea of a digital calculating clock for digital adding and subtracting (Wilhelm Schickard)	Wußing [111]
196	Programmable computer	Taking punched-card mechanisms as operation and variable cards/inputs	Babbage [112]
169	Symbolic logic	Formalizing reasoning	[104]
79	Abstracted model of structure and stepwise processing of computers	Algorithmic, controlled, memory-based processing of inputs which transform an initial to a final state (output), Turing's state machine; John von Neumann's architecture	Turing [107], Von Neumann [113]
78	Symbolic representation of technical systems	Applying symbolic language to relays and circuits	Shannon [106]
70	Inventing flexible technological memories	Utilizing electron properties for storing rewritable memories with (analog) technology (patent 1946)	Lavington [114]
68	Developing an algorithmic language	Going above machine code, creating the language PlankKalkül (Plancalculus)	Zuse [108]
10–20	Biocomputing	The operations of the cell and/or the structure of DNA, etc. are used as processing and storage units	Various researchers since ca. 1995

At that time the road to general abstraction and to the maximum reduction to the binary-number system was paved by giants of thought such as Francis Bacon (1561–1626), Blaise Pascal (1623–1662), and Gottfried Wilhelm Leibniz (1646–1716). The next step, i.e., a comprehensive mathematical analysis of symbolic, binary logic was elaborated by Boole (1815–1864) [104,105] and refined by Charles Pierce (1839–1914).

"Analog calculators are devices in which the variable occurring in the problem to be resolved are represented by continuous-variable physical quantities whose values are constrained by the device so as to obey the same mathematical or physical laws as in the problem to be solved" (see [101] (p. 158) and [115]). The ancient Greeks (150–100 BCE) had a clockwork mechanism of about 30 bronze gears that simulated orbits and calendars [116]. Lord Kelvin (1824–1907) modeled tide and temperature dynamics. Analog computers that work on continuous physical magnitudes and the electronics wave model or ballistic curves (in the context of anti-air defense) are ideal subjects. They call for a close relationship between the model and reality and the computational model (i.e., analog reasoning and modeling is the issue, done, e.g., by differential equations or trigonometric functions), whereas the continuous physical reality is rather a background layer. By contrast, digital communities (such as people from computing or data mining) tend to take (discrete) numbers as subjects. We may consider analog computers as their own stream of technological development that evolved largely from the "pre-World War II engineering culture that valued "know-how" more than "knowing" and continued to view engineering as more art than science. The research was mostly industry-driven and related to specific problems.

We do not deal in detail with quantum state computers [117–119] here. Quantum computers are still relatively far from large scale implementation. Quantum leaps are *digital by nature*. However, analog structures step in, e.g., by the wave concept and the location of electrons [120].

Biocomputers open a new chapter in the history of computing [121–125]. Scientists from the field of synthetic biology are looking at the individual cell from an information-processing and information-storage perspective [126,127]. The idea is to insert circular strings of DNA (plasmids) into *E. coli* cells. They have identified different plasmoids that can be assigned to all 16 binary Boolean operations. The plasmoids include promotor or terminator sequences that start or halt gene transcription, which affects a green fluorescent protein that functions as output genes. One groundbreaking idea is to use "recombinase enzymes, which cut and rearrange promotor and terminator DNA sequences" [39,128]. This causes the DNA to control something in the cell. The information is stored in a subunit of the living cell, which has a memory. The vision to create programmable cells with decision-making capabilities is forthcoming, and single cells of mammals can be programmed [129]. We may postulate that this development will call for completely new theoretical approaches for understanding biotic digital systems, e.g., that develop a mind and thus include organismic decisions.

The availability of seemingly unlimited big data causes scientific and social challenges. Big data usually emerge from different more or less known contexts; they appear in an abstracted digital, often decontextualized manner. Mostly, they do not allow for classical modes of scientific reasoning and validation (e.g., validation by experimental causal reasoning; [130]). The new scientific field of data mining [131] is an art rather than a science and "lies in the confluence of predictive analytics, statistical analysis, and business intelligence, using a plethora of statistical techniques and business intelligence" [132] and are usually post hoc analyses. This (i.e., misinterpretations) may cause scientific and societal vulnerabilities. From a science perspective, the question is how findings may be interpreted, how they may be related to theories, and what validation looks like. It is unclear what scientific standards and a clearinghouse of science might look like. From a societal perspective, data mining opens new areas of a digital divide. Questions include who owns the data and who has access to the data and to tools for analyzing them, among others. Another critical question is what knowledge must be taught through what type of instruction (including schools) in order to make this knowledge available to the average citizen.

3. The Techno-History of Digital Machines and Digital Environments E_D

This section takes a machine perspective [133]. E_D include a myriad of innovations from electronics, telecommunications, materials science, software engineering and many other fields of engineering.

3.1. Approaching Machine-Based Computing

Following the abacus (see Figure 3a), which was primarily a counting device and memory (as all calculations were done by mind), the first physical calculator was introduced by Napier (1550–1617). He constructed rods ("Napier's bones") that allowed for precise multiplication when using logarithmic addition and subtraction (with digital, discrete data) as a means of multiplication and division. Napier's require the manual positioning of bars according to certain rules that an operator must master.

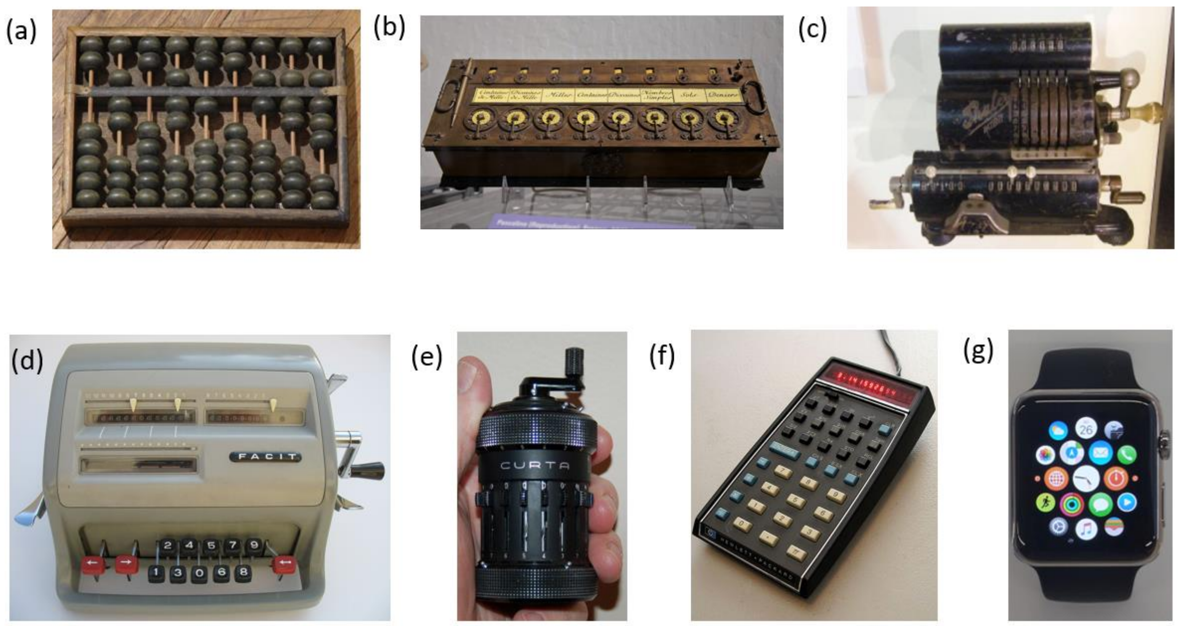

Figure 3. Public-use computers: (**a**) traditional abacus (upper section of image) and a wristband abacus (as artwork, abacus Bracele; lower section); (**b**) Blaise Pascal's 1642 two-species (addition and subtraction) numerical wheel calculator; (**c**) Facit Standard (1924–1933); (**d**) Facit CA1-13 electromechanical calculator (1957); (**e**) mechanical microcomputer, with 15 digits (Curta Type I; 6.5 cm diameter and 9 cm altitude, basic body, 360 g; 1957–1970); (**f**) HP-35 (1972), HP's first pocket calculator including trigonometric functions; and (**g**) Apple iWatch (photo: Susanne Wolke).

The first digital calculator was constructed by Blaise Pascal (1623–1662, see Figure 3b) and worked only for addition and subtraction. He considered this technology to be attractive enough for commercialization but finally produced only 20 machines [134]. Because he got bored of menial calculation, Gottfried Leibniz (1646–1716) constructed a complex, staggered, digital wheel-based machine. Leibniz's machine was commercialized, and had many direct successors. The Odhner calculator, also called TIM ("Time Is Money", see Figure 3c), was produced until 1947. Mechanical automated calculation machines that were produced until 1970 (see Figure 3d) and became ubiquitous in insurance companies, engineering, etc. Miniaturization became an issue but faced limits of downscaling mechanical clockwork technology (see Figure 3e). The pinwheel calculators were given electric motors and keyboards. The Swedish Facit AB calculator company noticed too late that new technologies were more efficient and went bankrupt [135] in the early 1970s. Since 1961 handheld calculators offered a completely new level of portable electronic calculators [100]. They got a final breakthrough with magnetic-card programmable calculators in 1974 (Figure 3f). In 2015, Apple iWatch provided a multifunctional micro-computer.

Historically, British mathematician Charles Babbage (1792–1872) was a key actor in the development of a functioning computer [100]. His Difference Engine transferred polynomial and logarithmic algorithms to mechanical machines. He also sought a nonhuman energy-driven full automaton to avoid humans having to press levers or rotate handles. Given the technology of 1822, he designed a steam-engine-driven iron wheel computer. His major technology contribution was his punched-card programmed Analytic Engine (see Table 2). Here storage was also a challenge. The Babbage machine had more than 1000 figure wheels capable of holding 40-digit signed decimal numbers each [136]. Herman Hollerith (1860–1929) brought about major innovations. He used an electric current to sense the punch-card holes [100].

3.2. Digital, Analog, and Bio-Computing

Konrad Zuse (1910–1995) built the world's first programmable digital electronic computer, in 1937. His first commercial computers worked exclusively with approximately 1600 binary electromechanical (mostly second-hand purchased telephone) relays, had a memory and an input–output unit, and were programmable. The speed of addition was relatively low (around 0.8 s). The 1940s were a decade of relay computers. The machines were huge. The invention of stored-program electronic computers required mastering the physics of the electron. When exploring cathode-ray oscillographs, vacuum tube electro-engineers could develop storage tubes such as flip-flop triodes. Storage (short-term) and information processing of large-scale computers in the United States and Britain, such as ENIAC, had about 18,000 not completely reliable tubes, 70,000 resistors, 10,000 capacitors, and 70,000 hand-brazed joints, and they still called for much mechanical logic. Storage was accomplished with punched or magnetic tapes [100].

ENIAC and similar computer frameworks, the von Neumann architecture [113], and Turing's [107] mathematical contribution to how a general computer paved the way for hardware construction. Mahoney [137] distinguishes between hardware and arithmetic design which is linked to the construction and use of computers. The highly reliable mainframe computers are currently the basic backbone of E_D, particularly for business and military proposes (including cyberwar and cyberterrorism), intelligence work, and space research programs. Therefore, much or most of the big data is not publicly available.

Digital preservation, i.e., long-term conservation, is a critical an issue. The threat of a digital time bomb [138] also became an issue, in particular for "under-resourced institutions" (e.g., in the developing world). In general, printed paper is still seen as a robust long-term storage source, in particular for preserving the cultural heritage. Digital systems have shown rapid technical aging, and preservation may become expensive if we extrapolate from that in 1986 about 1% of the worldwide communicated information was stored whereas in 2007 this was 16% [139]. Smart filtering systems and long-term strategies are a challenge. Currently, we are currently facing more of a "muddling through" than a well-considered long-term storage management perspective.

Currently, Internet of Things (IoT) is developing. IoT provides a digitally networked interconnection of everyday processes "which are often equipped with ubiquitous intelligence" [140] (p. 1101). Tiny Radio-frequency identification (RFID) modules that can be powered by external electromagnetic induction play an essential role in IoT. Cloud computing, a shared, ubiquitous, on demand availability of data and programs can be seen as a prerequisite of IoT.

From a machine perspective, velocity, memory capacity, and reliability are key criteria for computers. Energy consumption and efficiency became an issue [141]. A high-performance microprocessor consumes about 100 W of power, and large computers are facing critical cooling problems [41].

Analog computers steadily disappeared after World War II, at least from the academic platform. They became museum pieces [57] with the spread of the more highly esteemed digital technology and its advantages with respect to storage (which is a major deficit of the analog approach). There have been valuable applications in domains such as electric circuits and motors; military firepower; and aeronautical, aerospace, and nuclear projects; as well as in medicine when the interaction with the fuzziness of processes, e.g., noise in the system was essential and a fast, practical solution was wanted by "encapsulating the complexity in the [analog] structural complexity of the machine" [142]. By 1960 this technology, which was a product of industrial research and development related to specific problems rather than one of academia [101], "was pushed aside into just a few application niches" [143].

How far the integration of (components of) living cells in functioning computers has progressed is unclear. This may be because we are facing a promising, highly competitive field of technological development. Results are published after the submission of patents. Meanwhile, Zhirnov and

Cavin [41], leading scientists with the public–private Semiconductor Research Corporation, offer an excellent overview of the biosynthetic industry.

3.3. The Exponential Development of the Velocity/Density of the Central Processing Unit Is Coming to an End

Already in 1965 Intel's cofounder Gordon E. Moore [144] predicted that the progress (density) of transistors (defined as the numbers of transistors per circuit) would double each year [145]. Other digital quantities, such as data storage, processing capacity follow this empirical law [77]. Recently, Moore stated that this trend will flatten and come to an end in foreseeable future [145]. "The two fundamental limiting factors for severely scaled microsystems are the tunneling limit on the minimal size due to [the] small mass of electrons and excessive energy consumption in metal wires used for rigid interconnect systems" [41].

As the access to huge amounts of digital storage and the increase of processing (and thus communication), storage, and retrieval are the main characteristics of the digital revolution (see Figure 2), the slowing down of the speed of extension of storage capacity may push new forms of E_D such as biocomputing. Physicists and engineers are going to acknowledge the superiority of a cellular system with respect to spatial demands, memory storage density and magnitude, speed of processing, sensitivity, selectivity, reproduction time, and energy efficiency, and are therefore preparing for the 21st century, which is considered the century of biology. While accepting that brain performance is far above the trajectory of Moore's law, they see it as the only chance to learn from nature.

Computing technology can benefit from the tremendous progress of synthetic biology in DNA synthesis and sequencing, and one option is to integrate DNA two-bit memory systems with integrated semiconductors [41]. DNA is presumably the first mode of data storage in the world and among the most dense and stable information medium known [146]. A more ambitious route consists of referring to proteins that represent multivalued digital or analog logics. This would bring analog computing into "hybrid digital & analog information processing . . . (as, e.g.,) protein-based computing often represents and processes information in analog form . . . " [41]. This falls under the heading of cytomorphic electronics. There is a series of experimental demonstrations [147]. Two options are currently being explored practically. The first is that a cell is placed in a microenvironment with bi-directional multichannel interface periphery; the cell can be stimulated in a way that causes it to serve as an efficient computer. The other way is working with subcellular fractions. These are extracted, and molecular processes and machinery may be manipulated [41]. We may hypothesize that cell-based digital systems will be forthcoming rapidly as the window of Moore's law seems to be coming to an end.

4. Discussion

Technologies have changed the world. Experts in the field state that historically, there has not yet been any technological invention that altered all domains of life as fundamentally and as fast as digital technology. Or to pinpoint this: The digital revolution causes "threats so big that you cannot even talk about them" [148]. Contrary to the Industrial Revolution, which also had severe negative environmental impacts, it seems clear that the major impacts and threats of E_D are related to (normatively) unintended changes in social structures, including changes in human rights such as a loss of privacy.

Naturally, E_D provide a myriad of tremendous benefits for human systems. Yet, from a sustainable-development perspective, we have to reflect and manage unintended rebound effects, the passing of critical tipping points, or critical change rates that may endanger system-limit management [148] (p. 7). The prevention of collapses (i.e., vulnerability management) because of a lack of human adaptation [65] and the establishment of resilient systems [149] have been seen as core tasks of sustainability management.

The historic sections have revealed the tremendous speed of digital technology development starting with Boolean logic, Shannon and Turing's contribution and Zuse's first computer (see Table 2).

The miniaturization of technical digital computing processes underlying the exponential increase of storage capacity brought computers to the nano-scale and thus to the cellular scale (E_m, see Figure 1) of human engineering. This section highlights the propositions that are considered essential to the resilience of coupled HE_DS systems.

4.1. Digital Technologies Mitigate Natural Mutation-Based Variation and Become a Means of Evolutionary Intervention with Large Societal Impacts

Sections 4.1 and 4.2 start with the appropriation of nature, i.e., the unrelenting human drive to utilize and master nature on a new, i.e., cellular scale (E_m). Much of the current progress in biology and medicine relies on digital technology. The Human Genome Program is now entering a second stage as it shifts from genome reading to genome writing with the goals, among others, of creating organs for transplantation or targeted intervention in prenatal diagnoses and genetic modification of stem cells to avoid critical diseases [150]. We do not discuss why the opening meeting of the second stage of this project with entrepreneurs, policy leaders, and scientists has have been a secret, by-invitation-only program [151]. Nor do we refer to ethical challenges or moral concerns (which may bring us to genetically modified athletes in sports, [152]) related to genetically modified organisms (GMOs) that may call for a sophisticated intercultural analysis. Instead, using the example of genetically modified (GM) crops, we demonstrate the types of potential rebound effects that should become matters of investigation and anticipatory sustainability management.

The impacts of large-scale genetic modification should be monitored: One factor is that genetically engineered plants and animals may critically change the gene pools of certain sensitive species or ecosystems. This has already become the subject of a US Senate committee hearing [153] with a discussion of whether fast-growing genetically modified salmon (which may be not that robust against certain extreme environmental conditions) might affect the resilience of wild salmon [154,155]. In some ways, the spread of new gene vectors on a large scale [156] resembles the assessment of the impacts of invasive species. Thus, a lesson we may learn is that this calls for thorough, methodological, well-founded scientific research in order to avoid biased and erroneous conclusions [157–159].

Another concern involves the impacts of GM crops on the world's agrosystems. Here we mention only two issues. Forty centuries of organic farming [160] and breeding, particularly in Asia, have generated crops that produce a maximum yield for specific, sometimes agriculturally poor local soils, specific climate conditions, and locally available (organic) nutrients. The seeds planted were in the hands of farmers and publicly owned plant breeders; however, this situation has changed rapidly in the last twenty years. The global market share of the top 10 seed companies has increased from 30% in 2001 to more than 75% [161]. A critical rebound effect is that global market mechanisms do not allow for adjusting GM seeds to regional or farm-specific constraints. Thus, small local seed producers cannot compete, and smallholder farmers are forced to buy suboptimal seeds that provide lower yields than the local seeds they purchased formerly, as GM seeds provide high biomass only with high (amounts mineral) fertilizer inputs and fertile soils (which they often do not have). This case demonstrates that digital-technology-based innovations, such as GMOs, have a global market potential that may consequentially reorder local (seed) markets and result in further income declines for smallholder farmers by abolishing their participation in seed production.

One might argue that this situation can be considered independently of the digital revolution. However, let us briefly take another historical perspective. The invention of DNA as a twisted right-handed double helix by Watson and Crick [162] would be inconceivable without binary numbers. The reading and manipulation of GMOs is impossible without digital computers. We argue that GMOs generate a new level of the appropriation of nature that requires new definitions of patent exhaustion and perhaps also of common goods.

In Box 2 we present the Bowman v. Monsanto case which refers to the ownership of (digital engineering-based) seeds (which resist glyphosate-based herbicide). The case effectively demonstrates the trade-offs between the protection of intellectual property rights and antitrust policy, including the increasing dependency of farming on industry. The case also hints at the future technological options of industry-governed agriculture and fundamental changes in farmers' rights.

The message here is that digital-technology-based operations may affect agrosystems and related ecosystems and ecosystem-function-based economic services in a fundamental way on a large scale—and potentially on a global scale. This paper argues that threats and unintended rebound effects that may emerge from these types of processes call for intensive scientific investigation, and that the intentional, selective manipulation of gene and cell processes requires a careful assessment of potential rebound effects.

Box 2. From genetic engineering to industrializing the agricultural system: Bowman v. Monsanto.

Roundup: Eliminating weeds and making nutrients available for crops is a key to efficient crop production, and chemically produced herbicides have become effective agricultural tools. At the beginning of the 1970s, Monsanto invented Roundup, an effective, broad-spectrum glyphosate-based herbicide [163]. Unfortunately, this herbicide not only killed weeds but also harmed crops. Therefore, Monsanto engineered glyphosate-resistant Roundup Ready crops, created by placing a gene from glyphosate-tolerant soil bacterium into the genes of crops, e.g., soybeans. As a result, farmers who want to apply the herbicide must also buy the herbicide-resistant crops. In addition, the farmer is urged to sign various conditions of sale. These include planting the crop only in a single season and not producing seeds from the Roundup Ready seeds (or to express it in other term: further copies of boundless copies of it; [164]). Furthermore, farmers may be "contractually obliged to buy new seeds each year" [165].

Let's examine this case in greater depth. Vernon H. Bowman, a 70-year-old soybean farmer in Indiana, saw a loophole in Monsanto's rules. Instead of seeds from Monsanto, he bought them from a grain elevator, which offered them as a commodity [166,167]; they cost half the price of the Roundup Ready soybeans. When he sprayed them with Roundup, he noticed that they were resistant against the herbicide (as 94% of local farmers grew Roundup Ready beans; [168]). So he replanted the seeds from the grain elevator commodities, which were not bound to any post-sale restrictions by Monsanto. Bowman believed that Monsanto's intellectual property rights were not applicable in this case because of the patent exhaustion doctrine. He informed Monsanto [169], and Monsanto sued him. The Supreme Court of the United States delivered an interesting decision which supported Mosanto (see No. 11-768 Bowman v. Monsanto Co. [170]).

The case is of special interest as it may refer not only to self-replicating entities such as plants but also—in principle—to self-replicating digital products and systems in the future. It is also of interest, as Bowman argued, that soybeans are self-replicating by nature. Future generations of seeds are embodied in the seed, and if the exhaustion is not finished with the sale, future generations may not be owners of soybeans originating from Roundup Ready [166]. The Supreme Court supported Monsanto's view with economic arguments, for example, noting that allowing "Mr. Bowman's tactic would destroy the value of Monsanto's patent" [171].

Further technology options: In principle, industries have several options for protecting their intellectual property regarding GM crops. *Nature News* describes three ways that biotech companies might proceed (all citations in the paragraph refer to [172]). Option one involves sterile seeds, a "genetic modification that switched on production of a toxin that would kill off developing plant embryos." It is interesting that in 1999 "Monsanto's chief executive pledged not to commercialize terminator seeds". "A different option is to place the transgene under the control of a switch that must be activated by a proper chemical." This technology has been called "gene-guard technology." Option 3 is a variant of this. Instead of chemicals, nanobots, i.e., nanotech assemblers that switch on the growth of seeds, could be used.

The Roundup case (see Box 2) can be considered another step toward the anthropogenic governance of natural variation, i.e., of one of the basic principles of evolution. We hypothesize that every fundamental, human-made intervention has potential negative rebound effects, at least from a multilevel vulnerability perspective. For example, China's one-child policy can be considered an exceptional socially (and globally) responsible action. As a result of this policy, many families wanted to be assured of having sons, and this become possible through the use of medical technology. However, the increase in males in China's population has, in turn, increased that nation's crime rate [173,174].

4.2. Biocomputers Open New Horizons of Computing: Computers Get a Mind

The exponential increase in the density of transistors (and thus efficiency and miniaturization) in the last fifty years—almost exactly as predicted by Moore's law—is coming to an end because of nano-sized limitations [41]. This will be a key driver for the promotion of cell-based computers, which will have immense potential; however, as "semi-organismic" machines, they will perform according to other mechanisms. This will call for new, biotic knowledge, theoretical models, engineering, and rules for how to meaningful utilize and interact with these computers. Computers will get minds—or, to express this idea another way—computers will become decision makers [29,36] in the sense that their reactions will depend on a holistically (bio-logical) shaped reception of environmental information that is processed depending on the history and specific state of the biotic system, including non-human-made evolutionary mechanisms. What this means is absolutely unclear today, but it is absolutely clear that such mechanisms will be at work in the future and must be properly acknowledged in the present. We also expect that the logics of cellular circuits will most likely require new or extended forms of bio-logics (see, e.g., [126]) and thus may go far beyond the basic propositional logic.

4.3. The Biophysical Impacts of Living in Digital Environments Have to Be Monitored.

Section 2 identified several milestones and mechanisms of the material, biophysical layer of human systems H_m (see Figure 1) and of the sociocultural epistemic layer, H_S. Section 3 sketched the technological developments of E_D, which we conceive as a specific subset of the human environment. Both sections focused on the understanding of the velocity of changes of these systems and on the mutual interdependencies among these three systems. We can see (Table 2) that the invention of digit-based (binary, octal, decimal, hexadecimal etc.) place value number systems (see Formula (1)) of E_D took about a thousand of years, a remarkably long time. Then, after a period without essential innovation, with the beginnings of the Renaissance, we were facing a rapid sequence of abstractions, including general Boolean algebra and algorithm-based (e.g., logarithmic), programmed computing resulting in, e.g., von Neumann architecture.

Digital technological development started later than the mechanizing of computing, around 400 years ago. Computers became electromechanical machines, but the mastery of the electron in the late 20th century and semiconductor physics-based transistors provided a tremendous development of storage capacity. This was predicted in an amazingly precise manner by Moore's law in 1965. Naturally, other technological components such as powerful telecommunication bandwidths for global networked ICT, the ergonomic improvement of (convenient and functional and increasingly natural human communication like) input–output interfaces, rapid miniaturization, and the increase in velocity of computation, transmission, and retrieval were also important. However, the availability of economical and seemingly unlimited storage capacity and fast retrieval procedures account for this essential milestone. Thus, the year 2002 may be identified as the gateway/reversal point to the digital age (see Section 1.4).

A critical question emerging from this coupled-system analysis is whether the human biophysical system H_m is phylogenetically prepared for the rapid spread of E_D. Our concern refers to long-term impacts of ubiquitous interactions with virtual, digital information-based interaction on the human brain, mind, and social structures. To answer this question, we have to acknowledge completely different time scales related to the development of modern technologies (from a magnitude of a few decades to a few centuries), the development of abstracted epistemics by the mind (magnitude of 4000 years), and the slow (genetic, physiological) development with its milestones of the development of a voice box (larynx; around 50,000 years), or the formation of Homo sapiens (which presumably coincided evolutionarily with the mastery of fire about 250,000 years ago, i.e., about 2000 generations ago). We question what adaptations the human biophysical basis is challenged to accomplish.

The genetic code, the raw material of evolution, is developing very slowly. If we take estimates that emerge from natural mutation rates about human–chimpanzee speciation, a common descent from some ancestor goes back 3.6 to 6.6 million years ago [175]. Thus, we may postulate that the basic mental hardware (i.e., the DNA of brain cells) has not changed much in the last decades or centuries. However, given the growing knowledge about environmental epigenetics, we have to question whether we read evolution and (intergenerational) adaptation properly when looking exclusively at DNA sequences.

The growth of London's cab drivers' hippocampi demonstrates the environmental impacts on brain morphology, suggesting that parts of the brain may grow as a result of intense environmental interaction and demands. Findings on cybersickness (see Section 1.5) suggest that intense virtual interaction with demanding graphical, settings of physical (e.g., dense, irregular, and types of) stimuli may have a similar strong impact on the brain as the formation of cognitive maps by London's cab drivers. Whether this is assumed to be a phenomenon such as increasing muscle size through bodybuilding or whether it includes some epigenetic, intergenerational priming is not clear yet. State of the art knowledge of environmental epigenetics [176] suggests that the epigenetic effects (for an overview, see [29] (pp. 109–113)) of intense or excessive exposure to highly demanding E_D cannot be discounted [177–180]. In this context an analysis of excessive exposure to destructive, aggressive, or sexual content (e.g., in excessive video gaming) is of interest [181]. Against this backdrop, given the magnitude of environmental changes and acknowledging the precautionary principle, we suggest that environmental epigenetics and proper epidemiological studies should investigate the impacts of the ubiquitous spread and psychophysical alterations caused by E_D, best starting from the investigation of excessive use of digital technologies (see Section 4.3).

4.4. The Destruction and Emergence of Social and Economic Structures of the Digital World Require Effective Resilience Management

The digital revolution has caused, and continues to cause, a fundamental transformation of economic and social structures. E_D have made economics a global real-time issue. Thus, for instance, a nation-state-based accounting and taxation is dysfunctional. The national economic, legal, and presumably political systems are currently unprepared to regulate these economic systems and to facilitate what has been called intra- and intergenerational justice, another pillar of sustainability. This would change if new structures (meaning accommodations) for supranational taxation systems were to be introduced. Supranational systems (which have Kompetenz-kompetenz and may penalize deviants) are supposed to be "more effective in addressing non-compliance, and more likely to mediate the impact of power asymmetries on dispute settlement outcomes, compared to systems relying on state-initiated complaints only" [182].

The culture of the Internet is a global one, and access to the Internet is now sometimes seen even as a human right [183]. There will be something such as a global mind which has also been metaphorically called "Planetary nervous system as a citizen web" [148]. There is a huge potential that has—unfortunately—a large likelihood of not being used despite of many visionary statements about democratization and open access-based intellectual development in all parts of the world in (early) pro-cyberculture papers. However, theoretical and empirical studies draw a different picture. The same demographic and socioeconomic variables that induce general injustices related to income, education, race, age, and gender affect how digital media are used [148]. There is a strong inequality in the global information culture. Top universities have a different online access to a large number of high-quality scientific journals [184]. Countries that are not well connected "to a high-quality infrastructure and do not have skilled labor force, ... are locked out of the global economy and therefore slip more into poverty" [185]. Statements such as "wealth inequality has continued to increase since 2008, with the top percentile of wealth holders now owning 50.4% of all household wealth" [186] and "the richest 1% will own more than all the rest by 2016" [187] consistently convey the fact that social inequality is increasing on all scales. Computing machines have become subjects of commercial activities. Today, digital technologies are contributing to increasing rather than countering the current trends toward greater injustices in wealth. The knowledge of how to use ICT efficiently and the lack of physical access to these technologies matters.

There is not only evidence that the middle class—which has been a stabilizing strata in societies—is shrinking [188]; we may also suspect that small and medium sized enterprises—which are the backbone of most national industries, innovation, and wealth—may only survive if they adapt to this digital economy. This refers to new demands for a proper positioning in the global supply chain, the smart utilization of big data, and the efficient adaptation to integrative, digital management of inner company processes. "Big data . . . are now spreading like wildfire . . . The invention of computers is transforming service societies into digital societies .." and "50 percent of jobs in the industrial and service sectors will probably be lost within the next 20 years" [189].

In addition, the scaling down of human systems to groups, families, and individuals is cause for concern. The digital world has altered interpersonal communication [190]. Although cell phones have become ubiquitous, they are used mostly for brief written communications instead of talking directly. People are turning away from the people next to them for interacting by short messages. On the contrary, Skype communication allows global families to preserve their family bonds [191], and even to participate in domestic activities [192]. We have reported about the controversial effects of such behavior on well-being, making and keeping friends, social anxiety, etc. [193,194].

There seems to be much ambiguous change in interpersonal relations. Boundaries between the public and private, personal and professional, and what means friendship, and social relations are redefined [195]. There is strong evidence that social capabilities, i.e., the rules of communication, help to build friendships [148] and that the ability to read another's voice and behavior facilitates resolving conflicts and disputes. Perhaps empathy and bonds of affection are also changing if communication is done predominately by E_D. We know little about what these changes mean on a societal level, although there is evidence of a rapid change in friendship formation in that direct physical contact is becoming less important. Humans want to have computers as partners in child care [196]. What this means for the formation of the family and the community (i.e., for unsalaried, voluntary community involvement) or the maintenance or change in political involvement is unclear. We should also acknowledge that changes are interacting with the cultural matrix. Internet use seems to be very excessive in Asian cultures [75]. However, in each of the different human culture systems (individual, group, economic as well as non-economic organizations, etc.) will have different and partly conflicting interests and drivers for certain forms of E_D. This is why a multilevel analysis is needed here.

We may perhaps learn from history how to meaningfully cope with such a fundamental change from a precautionary and sustainability perspective. The Western world was shocked when the Russians were the first to send an artificial satellite around Earth in 1957. People became concerned that their academic programs, particularly in mathematics and engineering, were insufficient. This led to promoting education and research in the field, to the creation of new universities, and—as a monitoring program—to the International Educational Achievement Studies [197], followed by Pisa (Program for International Student Assessment). The idea is to monitor E_D-induced behavioral changes in a kind of international assessment of digitally induced behavioral and societal structure changes (see Conclusions: Proposition 3). Here we may learn in what ways social structures and potential are changing. Here, the term "behavior" has to be interpreted in a very broad sense to include value- and social norm-related elements required to establish a resilient society or democracy.

4.5. Protecting the Human Individual's Privacy Calls for a Comprehensive Vulnerability Analysis with Respect to Big Data Threats

The previous section focused on the resilience of social and economic structures. However, from a multilevel vulnerability perspective (see Section 1.4), the human individual—both as a single person and as a category—may be exposed to multiple threats due to big data and E_D. From a Western-culture perspective, a key issue is the protection of the general common-law right to privacy. This right was sought at the beginnings of the industrial age [198] and became part of U.S. law through various decisions of the Supreme Court [199]. You may argue that, both from an anthropological perspective [200] and a coupled-system perspective, big data (which are always in a gray zone with respect to ownership) fundamentally changes the individual's rights, integrity, and identity.

The days of anonymity and privacy are gone. The genetic code may be easily inferred and can become intentionally or unintentionally public [67]. The same holds true for medical data [201]. Purchasing behaviors, geographic locations, behavioral patterns, consumption patterns, and interactions, phone calls, etc. are all recorded. Your personal big data have become a means of representing and appraising someone. However, most of the data are stored in unknown places—owned by companies, institutions, or individuals you do not know—and you have no control over your data, which are "shrouded in legal or commercial secrecy" [202], or the company that owns and sells your data. Big data have a big potential for social and world governance. But at the moment, the world is far from consensus that individual data are trustfully and securely stored to avoid discrimination, stalking, and personal destruction.

Video recording called for new laws [203] that properly balance aspects of privacy, freedom, dignity, transparency, accountability and user control [204]. However, the protection of the human individual is not solely a European issue. Thus a global participatory platform has been suggested [205]. A smart and powerful idea is the "data protection by design" [206]. This in particular refers to the smartphone, which almost has the status of a 24-h diary. Industry, criminals, but also secret services have an interest in getting access to these data. For securing privacy, the smartphone provider Apple's 2014 operating made "encrypting all third-parties data stored on the customer's phone [the] default [207]. This encryption was legally attacked by the U.S. government, following the FBI's intervention. Breaching the individual's privacy barrier was judged inferior to the need for access to the phones of terrorists, kidnappers, and criminals. Based on this, we propose that the idea of the individual's right to privacy and of protecting personal data is highly endangered by ED. The idea of data protection by design is technologically possible. Here society is facing a trade-off with public security.

5. Conclusions

We summarize the discussion along three propositions. The first relates to impacts (on all levels of human systems) that emerge from digital-technology-based manipulations on the cellular level (see Sections 4.1 and 4.2).

Proposition 1: *Human evolution has attained a new stage as a result of the digital, engineering-based manipulation of natural variation at the cellular level (i.e., directed evolution vs. random mutation) and due to biocomputers that include living cells. Biocomputers fundamentally change the nature of digital environments. They call for new knowledge and theories of programming and logic, as well as an understanding of how to utilize these new types of hybrid beings.*

We have shown that, in the case of Roundup (see Section 4.1), genetic manipulation at the DNA level has the potential to cause a myriad of impacts on social and economic systems in the higher scale of human-environment systems.

The next proposition refers to the level of the individual (see Sections 4.3 and 4.5). We identify biological, epigenetic, and sociocultural threats that urge investigation and management.

Proposition 2: *Environmental epigenetics and proper epidemiological studies should investigate the psychophysical impacts resulting particularly from the excessive use of digital information by sensitive individuals. In addition, a wide range of disciplines from the humanities and social sciences should assess in what ways the individual's right to privacy is endangered by* E_D *and big data.*

We should note that, technologically, solutions using encryption (that support privacy) by design may conflict with the interests of intelligence agencies and others. Here, we may encounter conflicts between the goals of the individual and those of higher social systems. The third proposition refers to research on the rapid change of human systems and their capabilities (see Section 4.4).

Proposition 3: *The rapid spread and intense use of E_D may have potentially severe impacts on communication and the formation of social and economic structures on all levels of human systems.*

The message of each of these propositions is that not only beneficial effects but also the potential for unintended, societally undesirable short-, mid-, and long-term effects should be investigated. Vulnerability and resilience management of digital environments should come under scrutiny, and these will require high-quality interdisciplinary work and well-funded, large-scale research programs. These propositions highlight several areas that deserve the focus of national and international research programs that will enable us to understand and manage the trade-offs resulting from the benefits and the threats of utilizing new E_D. A particular challenge will be to develop methods for assessing these vulnerabilities and increasing the adaptive capacity of human systems for maintaining viability in a rapidly changing environment [208]. Considered as a common feature of technological development, this may not be perceived as especially new or innovative. However—as this paper has attempted to demonstrate—the depth and pace of innovation of the digital revolution are characterized by historically unknown speed, multitude, and complexity. This paper and its propositions can, it is hoped, help to structure the complexity and priority formation of future research.

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