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ORIGINAL PAPER

Why converging technologies need converging international regulation

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Abstract

Emerging technologies such as artificial intelligence, gene editing, nanotechnology, neurotechnology and robotics, which were originally unrelated or separated, are becoming more closely integrated. Consequently, the boundaries between the physical-biological and the cyber-digital worlds are no longer well defined. We argue that this technological convergence has fundamental implications for individuals and societies. Conventional domain-specific governance mechanisms have become ineffective. In this paper we provide an overview of the ethical, societal and policy challenges of technological convergence. Particularly, we scrutinize the adequacy of domain-specific governance mechanisms in the face of such integrated technologies and highlight their growing ineffectiveness. Furthermore, we propose a comprehensive governance framework that is anticipatory, inclusive, and resilient. Central to this framework is the principle of participatory governance, which calls for a proactive engagement of all stakeholders, including those from marginalized and vulnerable populations, ensuring that their voices and concerns shape the trajectory of technological development. The framework emphasizes the need for protective measures that preemptively address potential risks and inequities that may arise from the adoption and integration of emerging technologies. Based on a detailed analysis of case studies and current governance models, we present and discuss a set of ten actionable recommendations. These are designed to facilitate the transition towards a governance approach that not only respects individual autonomy and privacy, but also fosters a collective responsibility towards sustainable and fair technological progress. By placing human dignity, societal welfare and the protection of the most vulnerable at the center of technological innovation, we advocate for a future where convergence is synonymous with progress that is both ethically grounded and universally beneficial.

Keywords Converging technology · Artificial intelligence · Gene editing · Nanotechnology · Neurotechnology and robotics · Regulation · Policy · Human rights

Nano/Digi/Bio/Neuro: what are converging technologies?

Since the beginning of the 21st century, the increasing interconnectivity of computing systems and networks combined with the rise of intelligent automation have exerted a rapid change in technology, industries, as well as societal patterns and processes. Concurrently, the embedding of sensor and computing capabilities into everyday objects (a phenomenon known as the *Internet of Things* or *IoT*) (Wu et al., 2022) and their integration into living organisms (*Internet of Bodies*) (Celik & Eltawil, 2022) as well as the increasing reliance on computational modelling in nearly every field of human activity, have blurred the lines between the physical, digital, and biological worlds.

As a consequence of that, once unrelated technologies such as digital computers, sensorics, artificial intelligence (AI), gene editing, neurotechnology, medical prosthetics, and nanomaterials have become increasingly inter-dependent and applicable across multiple domains. This phenomenon, known as “technological convergence” or “converging

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technologies" (CTs), represents a socio-bio-technical paradigm shift, marked by the ubiquitous distribution of computational and sensory capabilities, and the consequent dissolution of domain-specific boundaries – between once unrelated fields of technological innovation and their application domains. For example, AI algorithms and computational models have become essential tools for scientific research and innovation in nearly all fields of knowledge production and technology development, from medicine to banking, from transportation to scientific discovery. Further, medical technologies are increasingly equipped with sensing technologies and computing capabilities, making it possible to collect and share vast troves of biometric, physiological, and behavioral data – either invasively (through medical implants or swallable, injectable, absorbalbe, or self-replicating technologies) or "non-invasively" (via wearables or applications based on smartphones or smart devices). This close proximity and functional integration between the human body and digital technologies can be referred to as a [bio-]cyber-physical system ([Bio-]CPS), which is an integrated system consisting of both cybernetic and physical-biological components.

Converging technologies are a multidisciplinary enterprise. As Wallace put it: "If the Cognitive Scientist can think it, the Nano people can build it, the Bio people can implement it, and the IT people can monitor and control it." According to the World Economic Forum "[w]e're entering the era of the "Internet of Bodies" [IOB]" which makes it possible to „collect our physical data via a range of devices that can be implanted, swallowed or worn" (Liu, 2020).

The profound impact of convergent technologies on the research and development landscape, as well as its potential for reshaping social relationships, business models, and societies, has been assessed inter alia by the seminal work of Mihail Roco. Almost twenty years ago, Roco predicted that technological convergence will catalyze significant advancements in transformative tools, new products, and services, markedly enhancing human capabilities and societal achievements (Roco, 2005). According to his point of view, this integrative approach would focus on human needs and aspirations, particularly within the biomedical and cognitive domains. For Roco, the mastery of nanoscale matter and the advancements in systems thinking, mathematics, and computation would reveal the intricacy of the resulting complex, hierarchical systems. The implications of this convergence would manifest in revolutionary products, increased human performance, and the evolution of organizational and business structures.

Despite the growing interest in this phenomenon of socio-technological integration, the concept of technological convergence has long been lacking a clear definition. Roco described converging emerging technologies as "the synergistic combination of nanotechnology, biotechnology, information technology and cognitive sciences (NBIC), each of which is currently progressing at a rapid rate, experiencing qualitative advancements, and interacting with more established fields such as mathematics and environmental technologies" (Roco, 2006). More recently (and succinctly), Silva (2018) referred to it as "a confluence of technological capabilities" (Silva, 2018). However, neither definition elucidates the causes and effects of this synergistic combination or confluence, nor does it capture the essential implications of this sociotechnological trend, namely the disappearance of a sharp separation between the biological-physical and digital-virtual domains.

To overcome this conceptual impasse, in this paper we define "technological convergence" as a new socio-bio-technical phenomenon involving three distinctive characteristics:

A. the increasing ubiquity and pervasive distribution of sensing and computing capabilities across both physical objects and biological organisms;
B. the erosion of a clear separation between the physical, digital, and biological domains due to emerging technologies such as artificial intelligence (AI), gene editing, nanotechnology, biomedical engineering, neurotechnology and robotics;
C. the increasingly frequent co-occurrence of the technologies listed above and their large-scale spreading in ways that may be hard to detect, protect from, and manage.

While a closer integration between formerly unrelated technologies promises significant contributions to socio-bio-technical innovation and human well-being, it also creates critical challenges for ethics and governance. Due to their potential for social and biological disruption, the socio-bio-technical phenomena described above have often been referred to as "the fourth industrial revolution", which would lead to the "society 5.0". These labels reflect the rapid transformations elicited by converging technologies, which are often expected to result in the ubiquitous interconnectedness, massive data exchange, and pervasive automation of the technologies and processes that include [Bio-]CPSs. Already in the 2000s, Roco observed that the incremental introduction of NBIC technologies necessitates an assessment of both immediate and long-term societal and ethical challenges. These include issues of privacy in the bio-digital world, the toxicity of new materials, and broader issues of human integrity, dignity, and welfare.

Almost twenty years after Roco's predictions, the revolutionary potential of converging technologies is starting to materialize in nearly every domain of human activity. In the energy sector, smart grids, which integrate renewable energy sources, AI, and IoT, are promised to promote efficient energy distribution and consumption, while also supporting the monitoring and management of city-wide energy usage (Abir et al., 2021). In agriculture, drones, satellite imagery, and IoT devices are used to monitor crop health, soil conditions, and weather data (Naresh & Munaswamy, 2019). This data is then processed using AI algorithms to optimize farming practices, reduce waste, and enhance crop yields. In urban development, the integration of IoT devices, AI, and data analytics is leading to the creation of smart cities (Helbing et al., 2021; Silva et al., 2018). These cities use sensors and machine learning to optimize traffic flow, energy consumption, waste management, and even law enforcement activities, aiming to make urban living more efficient and sustainable. In healthcare and medicine, the convergence of NBIC is revolutionizing healthcare (Tian et al., 2019). Personalized medicine paradigms based on pharmaceutical genomics allow one to tailor treatments to an individual's genetic makeup, while wearable devices and implants can monitor vital signs and deliver drugs or electric waves as needed. Artificial organs are being developed using a combination of such technologies.

With the actualization of converging technologies, a complex matrix of societal and ethical issues is also being actualized. Building on the seminal work of Mihail Roco, this paper explores profound societal impacts of converging technologies and critically examines the need for converging international regulation of CTs. By synthesizing the major ethical, societal and policy issues surrounding CTs, this paper aims to contribute to an urgent and important discourse by highlighting emerging socio-technical complexities and proposing a balanced framework for governance. The central question driving this inquiry is: What are the implications of unregulated technological convergence, and how can converging international governance be effectively implemented to mitigate risks without curtailing innovation?

To structure this exploration, the manuscript is organized as follows: First, we review the current state of CTs and their applications across various domains. Subsequently, we delve into the ethical and governance challenges posed by CTs, drawing on existing debates and identifying the primary concerns of proponents and opponents of CT regulation. Third, we propose a set of criteria for when and how international regulation might be applied to CTs, informed by case studies and best practices in technology governance. Finally, we conclude with a discussion of the findings and offer recommendations for policymakers, industry stakeholders, and the broader international community.

Literature screening

The area of converging technologies is a relatively recent, emergent area of science and engineering. Therefore, this paper aims to reflect the state of the art of this field. For this purpose, we conducted a rapid review of the scientific literature on converging technologies and their associated ethical and societal implications. We searched the *Web of Science* database on September 27, 2023, using the following search query "Converg* Technolog*" OR "Internet of Bodies" OR "Internet of Humans" OR "Internet of Nano-Things" OR "Nano-Neuro-Technolog*" OR "Smart Dust" OR "Neur* Dust" OR "Neur* Rights", which retrieved 5,464 papers. A complementary search for "Internet of Bodies" OR "Internet of Humans" OR "Neur* Dust" OR "Neur* Rights" resulted in 64 papers. Combining these queries with AND "review" gave 290 and 8 papers, respectively, i.e., 298 papers altogether. We removed duplicates and checked for eligibility and relevance. Our paper provides a reasonably short summary of the research covered by these papers, with a focus on reviews and publications with high scientific impact, particularly those addressing ethical, political, or legal issues.

From a terminological perspective, it should be noted that converging technologies are often discussed in conjunction with the so-called "Internet of Humans"(Iaione et al., 2019) or "Internet of Bodies" (Arbia et al., 2015), which in turn are possible applications of the Internet of Nano-Things (Akyildiz et al., 2020; Akyildiz & Jornet, 2010) or Internet of Bio-Nano-Things (Akyildiz et al., 2015). Here, data may be wirelessly transmitted between bodies with the help of technology. The information transfer may involve technologies such as quantum dots (Gill et al., 2008) or optogenetics (Han et al., 2022).

What can converging technology do?

The increasing minitiaturization of sensor technology has made it possible to embed sensing capabilities into everyday objects and, more recently, even human bodies. For example, digital pills are an innovative drug-device technology that permits to combine traditional medications with a monitoring system that automatically records data about medication adherence as well as patients' physiological data (Martani et al., 2020). In the future, sensor technology is expected to reach nano scale, which implies components sized from 1 to 100 nanometers (Satalkar et al., 2016). This will enable novel opportunities for physiological monitoring of the human body as well as novel medical and extra-medical technological solutions based on nanoelectronics and biomaterials.

In this connection, magnetite particles (Maher et al., 2016) and graphene-based nanoparticles (Bramini et al., 2018) have been explored as substances of interest for interfacing with human cells including neurons, a process sometimes referred to with the labels “smart dust” or “neural dust” (Opris et al., 2020; Seo et al., 2016). Research at the interplay of genetic engineering and optogenetics has shown that engineered light-switchable RNA-binding proteins allow for optogenetic control of ribonucleic acid (RNA) function and metabolism (Liu et al., 2022). Furthermore, directed energy technologies could make it possible to read out distributions and movement patterns of nanoparticles by refraction or diffraction, thereby revealing microstructures and activity patterns of organic matter, including bodily organs (Li et al., 2022). Among those, nano-enabled neural interfaces hold potential for interrogating and interfacing the brain with greater resolution (Acarón Ledesma et al., 2019). Although readability is currently limited, it will likely increase as technology progresses.

On-going research suggests that these or similar approaches may also be used to detect diseases more promptly and even remotely (Akyildiz et al., 2020). In parallel, wireless nanomedicine approaches show promise to complement brain) tumor therapies and reduce cancer recurrence (Ho & Zhang, 2022).

[Bio-]CPSs are intended to deliver massive amounts of detailed data for personalized treatments in the area known as precision medicine (Adir et al., 2020; Patel & Lieber, 2019). One aim is to create highly accurate pictures of our bodies and minds, called “digital twins” (Helbing & Sanchez-Vaquerizo, 2022). These will allow one to study possible effects of medical interventions on a specific individual, before they are conducted, and to take a personalized course of action.

In the field of neurotechnology, the miniaturization of electrodes (Steinmetz et al., 2021) together with rapid advances in AI for brain data analysis (Mostapha & Styner, 2019) and in classification for brain-machine interfacing (Olsen et al., 2021) is radically improving brain activity mapping and analysis, both retrospective and predictive. On the long term, similar models could be applied to the semantic decoding or manipulation of mental states (Carrillo-Reid et al., 2017; Huth et al., 2016; Tang et al., 2023). In fact, large-scale brain initiatives such as the USA Brain Initiative (Insel et al., 2013), the EU flagship Human Brain Project (Amunts et al., 2016) and the China Brain Project (Poo et al., 2016) are attempting to combine basic neuroscience with advanced neurotechnology and brain-inspired computing.

The application of converging technologies is not restricted to reading data about human physiology and behavior, but also to leveraging such information for the pursuit of physiological, psychological and behavioral change. Applications may range from healing diseases such as cancer (Ayuso et al., 2022), mitigating the cognitive or affective symptoms of some psychiatric disorders, to eliciting behavioral change among people with eating disorders such as anorexia nervosa or traumatic disorders such as PTSD. For example, the miniaturization of robotics platforms has led to numerous microrobot and nanorobot applications that leverage precision medicine (Soto et al., 2020). Similarly, neurotechnologies such as deep-brain stimulation (DBS) and transcranial magnetic stimulation (TMS) are being used to mitigate the tremor symptoms of Parkinson’s disease and the mood imbalances caused by major depressive disorder (Cash et al., 2021; Limousin & Foltynie, 2019). In the future, behavioral change programs may be applied not only to people with psycho-behavioral disorders, but also to healthy subjects, which raises substantive ethical questions. For example, the use of converging technologies for the purpose of human sensory and cognitive augmentation (Cinel et al., 2019), i.e. the targeted upgrading of human sensory and cognitive capacities, is being pursued with the ultimate goal of transcending natural human abilities, a phenomenon known as *transhumanism* (Frodeman, 2019).

Note that many of the afore-described use cases are still in the development stage. Hence they will have to pass various feasibility and quality checks and overcome translational barriers in the future. However, in recent years, attempts to use converging technologies for purposes such as “human enhancement” (Gordijn, 2006) or “human augmentation” (Raisamo et al., 2019) have shown an increasingly realistic potential. This has been addressed, among others, in a recent publication by the UK Ministry of Defence (UK Ministry of Defence, 2021). In particular, this remarkable report observes that “[r]ecent advances in the life sciences and related technologies have led to the emergence of the interdisciplinary field known as human augmentation which has the potential to disrupt every aspect of our lives” (p.11). The report takes a proactive stance, arguing that “[w]e cannot wait for the ethics of human augmentation to be decided for us, we must be part of the conversation now” (p.13). At the governance level, the report observes that “[n]ational and international governance will be challenged by the myriad of implications of adopting human augmentation technologies. This could lead to a new arms race and inter- and intra-state tensions if not carefully managed through early and regular dialogue” (p. 13). Finally, the report argues that “[d]efence will need to develop a more effective relationship with those who work in the life sciences as the dual-use nature of emerging human augmentation technologies becomes clear” (p.14).

The dual-use problem of converging technologies

While creating ample opportunities for improving health, extending human abilities, and expanding life spans, converging technologies also create opportunities for dual-use. As defined by the European Commission, "[d]ual-use items are goods, software and technology that can be used for both civilian and military applications".[1] They may pose threats to public health, individual safety, or national security. In more general terms, dual-use can also refer to any technology, which can satisfy more than one goal at any given time, including both benevolent and nefarious goals. For instance, state actors may coopt converging technologies with the purpose of implementing novel forms of behavioral surveillance and control. By gaining access to data from technologies such as consumer neurodevices or sexual health apps, for instance, state actors may surveil highly sensitive information such as neural and reproductive information. Similarly, the availability of such novel and continuous data sources may be utilized to achieve more advanced forms of *profiling, social scoring and targeting*. While this risk applies to any state actor, technologically advanced autocratic countries are particularly at risk of establishing some form of *technological totalitarianism*. Finally, state actors may utilize converging technologies for non-peaceful aims, particularly in the context of *hybrid wars* (Almäng, 2019) (see Table 1), i.e. armed conflicts that combine different kinds of warfare, which may include cyber-warfare and nanowars.

Note that non-state actors are also likely to engage in the intentional repurposing of converging technologies for non-benign aims. For example, as computing capabilities are increasingly embedded in biological systems such as human bodies, biology becomes subject to the same vulnerabilities as information technology. These include the risk of malicious hacking, unauthorized data extraction, digital manipulation etc. Malevolent individuals or organized criminal groups are likely to exploit these vulnerabilities in manners analogous to current forms of *cybercrime and cyberterrorism*. [Bio-]CPSs that have reportedly been vulnerable to malicious hacking include neural interfaces (Ienca & Haselager, 2016) and cardiac pacemakers (Baranchuk et al., 2018; Best, 2020).

Table 1 Dual-use risks of converging technologies

Risk	Examples of converging technologies that might enable it
Novel forms of behavioral surveillance and control (e.g. in-body), technological totalitarianism	Digital pills, wearables, neurotechnology, microelectronics, affective computing
New kinds of profiling, scoring, and targeting	DTC genetic tests, digital pills, wearables, neurotechnology, neuroelectronics, emotion AI
New forms of hacking, cybercrime, and privacy threats	Emotion AI, neurotechnology, personal reproductive technologies, hacking of wearable or implanted human-machine interfaces
Military cooptation	Synthetic biology, AI, neurotechnology

While the dual-use problem is inherent in any technology, the dual-use challenges raised by converging technologies are novel from a variety of perspectives.

First, converging technologies such as digital pills, nanoparticles, nanorobots, or neural interfaces may enable not only exogenous surveillance (i.e., the *trac(k)ing of people* everywhere), but also endogenous or *in-body surveillance*. Second, converging technologies such as affective computing, immersive environments and neurotechnology may enable novel forms of *mental surveillance and influence*, as they may enable more direct and predictively accurate processing of mental information, such as information about cognitive and affective states. Third, as mentioned earlier, converging technologies that enable [Bio-]CPSs expose biophysical systems (including living organisms) to similar risks and vulnerabilities that computer systems struggle with every day. Fourth, technologies that manipulate matter at the micro- and nano-scale are harder to detect and monitor. Hence, it is expected to be more difficult to prevent their cooptation for nefarious aims by state or non-state actors, e.g., their exportation as dual-use goods. In particular, those operating at the quantum scale may display quantum mechanical effects, hence exhibit special properties of matter, which occur below a given size threshold.

Even more fundamentally, converging technologies urgently require a foundational conceptual transformation of the notion of dual-use. Conventional dual-use problems involve the risk that a certain technology developed for a certain purpose and a certain area (e.g., the civilian domain) is coopted for a different purpose and/or applied to a different area (e.g., the military domain). These conventional dual-use problems may be mitigated through expert control policies such as those elaborated by the Swiss State Secretariat for Economic Affairs[2] and the export control system of the European Commission[3].

Such policies typically involve the creation of lists of dual-use items, common export control rules and compliance measures for exporters and brokers, as well as other

[1] https://policy.trade.ec.europa.eu/help-exporters-and-importers/exporting-dual-use-items_en.

[2] See: https://www.seco.admin.ch/seco/en/home/Aussenwirtschaftspolitik_Wirtschaftliche_Zusammenarbeit/Wirtschaftsbeziehungen/exportkontrollen-und-sanktionen/exportkontrollpolitik.html (last retrieved: August 7, 2022).

[3] See: https://policy.trade.ec.europa.eu/help-exporters-and-importers/exporting-dual-use-goods_en (last retrieved: May 22, 2023).

rules aimed at mitigating the proliferation of weapons derived from non-military technologies. However, sectorial control of different domains is not expected to be effective, given the very nature of converging technologies spanning across different domains such as nanotechnology, biology, chemistry, physics as well as information and communication technologies.

Recent failures in international governance, such as the United Nations' inability to establish a regulatory framework for autonomous weapons (Rosert & Sauer, 2019) indicate the difficulty of governing converging technologies. The dual-use potential of nano-technologies and nano-neuro-technologies may pose even greater challenges. In an increasingly politically polarized and over-populated world, the dual-use of converging technologies may generate novel threats to life and health. The frequency and severity of threats is likely to increase with the increasing power and pervasiveness of applications of converging technologies.

The above challenges of converging technologies are further exacerbated by a well-known problem in technology governance: the pacing problem. This concerns a mismatch between the speeds at which technology and law progress. While emerging technologies are developing at an ever-accelerating pace, legal mechanisms for potential oversight tend to be slow (Marchant, 2011).

Mind the (regulatory) gap

Transferring methods such as ubiquitous sensing and micro-computing from production and supply chains to human bodies and brains may have highly transformative effects on societies and what it means to be a human. It raises fundamental ethical-regulatory challenges. Continuous monitoring and research are needed to assess whether and when the benefits of converging technologies outweight their risks.

We argue that, in the light of its socio-technical novelty, cross-domain nature and disruptive potential, converging technologies need converging international regulation. Current legal frameworks, although useful to regulate each technological application individually, are not sufficient to deal with technological convergence for three main reasons.

The first reason is the limited bandwidth and purview of technology policies, most of which are either domain-specific (e.g., the medical device regulation) or technology-specific (e.g., the recently drafted EU AI Act). However, as we mentioned above, converging technologies are inherently cross-domain and technologically hybrid, as they bring together multiple technological systems to produce complex functionalities and systems that interfere with multiple domains of human life and activity. Domain specific regulations are likely to become ineffective in the light of the cross-domain nature of nanotechnologies and their possible applications. Therefore, there is a need for policy bodies that encompass the whole converging technology spectrum. An example of this is the OECD Working Party on Biotechnology, Nanotechnology and Converging Technologies (BNCT), which aims to contribute original policy analysis on converging technologies to the global community. However, this has not yet resulted in internationally binding regulations.

The second shortcoming pertains to the fact that today's *de jure* risk categories are often insufficiently comprehensive to address the *emerging* risks of converging technologies. Nanotechnology offers an interesting example. Due to concerns about toxicity (Maher et al., 2016; The, 2007), i.e. their potential to *cause* diseases, nanomaterials are now mostly tested for *chemical* incompatibility with organic matter. However, there are insufficient risk assessment standards concerning possible aggregation effects or long-term interaction effects of nanotechnology with *radiation*, despite the fact that this interaction is the underlying functional principle of the IoT, the Internet of (Bio-)Nano Things (Zafar et al., 2021), and the Internet of Bodies. Similarly, neurotechnologies are evaluated for their safety in terms of biomedical risks (e.g., risk of post-implant brain infection or bleeding), but not for possible unintended impacts on subjective experience and personal identity (a problem increasingly referred to as mental integrity (Douglas & Forsberg, 2021; Ienca & Andorno, 2017)).

Non-binding frameworks such as ethical guidelines and the principles of responsible engineering and value-sensitive design (Jacobs et al., 2021) may offer a more comprehensive approach and guidance. However, it is unclear if they would have sufficient normative power.

The third reason is that existing or emerging legally-binding governance frameworks operate either at the national level (such as the Chilean Neuroprotection Bill (Guzmán, 2022)) or a supra-national level (e.g. the European Commission's AI Act (Veale & Borgesius, 2021)). However, these regulations cannot be enforced outside of the boundaries of the respective countries or supranational political unions, hence constraining the effectiveness of those laws in protecting their citizens worldwide. Since the potential effects of converging technologies are global, but current regulations are not, converging global governance is needed.

Closing the regulatory gap

The issues discussed above show that existing regulations are currently either insufficient or inadequately applied to address the challenges of converging technologies. However, besides the political-diplomatic avenue, it is possible to confront the issues by taking legal action, based on the international court system. In fact, despite a lack of specific laws, there are established legal principles and ethical provisions that, if adequately interpreted and applied, would draw "red lines" and lay the foundations of an international governance framework for converging technologies. We, therefore, urge political and legal actors to take action on the afore-mentioned pressing issues based on the following ten established principles (see Table 2):

First, from the point of view of the Planetary Health agenda and the Sustainable Development Goals (particularly goal 3 on health), we call for a broader interpretation and definition of toxicity vs. bio-compatibility as to include also possible interaction effects, such as those involving radiation. Furthermore, the implementation of nanotechnology in human bodies should be reversible and revertible, hence, nanoparticles should be bio-degradable within a reasonable period of time, not just bio-compatible. Further requirements are implied by the UN Charter of Universal Human Rights.

Table 2 Ten ethical principles to establish effective governance of converging technologies and a converging international regulatory framework

Principle	Recommendation
1	Broader definition of toxicity and bio-compatibility; reversible implementation of nanotechnology; implications of UN Charter of Universal Human Rights.
2	Inspection for violations of Biological and Chemical Weapons Conventions; consideration of expansions to address neuro and nano technologies.
3	Scrutiny regarding military cooptation of nanomaterials and optogenetic technologies based on the Geneva Weapons Convention.
4	Transfer of cybersecurity and security principles of critical infrastructures to protect against unauthorized interference with body and mind functions; punishment for hacking at least comparable to hacking of cyber-infrastructures.
5	Handling of digital twins at least in accordance with the right to protect one's image; development of platforms supporting informational self-determination.
6	Development of a new ethical and legal framework for the body-mind-machine continuum based on the Nuremberg Code and the Helsinki Declaration.
7	Guarantee of personal integrity and privacy in the technological scenario of converging technologies; overcoming of emerging privacy threats and introduction of neurorights.
8	Governance approaches and regulations focusing in particular on the protection of vulnerable people and under-represented groups.
9	Determination of international solutions through transparent, fact-based, and participatory decision-making processes.
10	Identification of a suitable socio-technical framework to enact reforms and establish a new social contract.

Second, the use of converging technologies should always be inspected for possible violations of the Biological (BWC) and Chemical Weapons Conventions (CWC). Since converging technologies involve the merging of biological and digital elements, logical expansions of the BWC should be considered. The recent discussion of neuro-nanotechnologies by the UN Office for Disarmament Affairs during the 9th Review Conference of the BWC underlines this need and marks a step in this direction.

Third, the Geneva Weapons Convention, whose Protocols I and IV are aiming to protect against non-detectable fragments and laser weapons, respectively, call for enhanced scrutiny regarding the military cooptation of nanomaterials and optogenetic technologies.

Fourth, the principles of cybersecurity and security of critical infrastructures should be transferred from the hacking of devices to the hacking of bodies as to protect against the unauthorized interference with functions of the body and mind. Such interferences should be punishable in a manner that is comparable to or greater than the hacking of cyber-infrastructures, especially if they violate principles of informed and voluntary consent.

Fifth, from an Intellectual Property Rights (IPR) perspective, digital twins should be handled at least in accordance with the right to protect one's image (Helbing & Sanchez-Vaquerizo, 2022). The security and IPR issues mentioned above call for the development of platforms supporting true informational self-determination, i.e., platforms that allow everyone to determine the rules that specify what kinds of personal data may be used by what categories of data users for what kinds of purposes.

Sixth, we call for the development of a new ethical framework for the whole body-mind-machine continuum. This framework should be multimodal (e.g. capable of operating in many modes of activity or occurrence) and multiscalar (e.g. operating at multiple scales, from the nano-scale all the way up to the macro-level). This framework should be based on fundamental ethical codes such as the Nuremberg Code and the Helsinki Declaration. In particular, the Nuremberg Code's pronounced focus on voluntary consent and respect for the person offer a solid basis, from which ethical and legal principles can be derived.

Seventh, the protection of personal integrity and privacy should be also guaranteed in the ever-evolving technological scenario of converging technologies. For example, emerging privacy threats to mental privacy and reproductive privacy should be overcome. Applications of converging technologies for the purposes of mental influence and behavioral control pose a high risk of violating personal freedoms and rights. Whenever existing normative provisions are insufficient to mitigate these risks, the introduction of neurorights (Ienca, 2021; Ienca & Andorno, 2017; Yuste et al., 2017) such as cognitive liberty, mental integrity, and mental privacy should be pursued.

Eighth, governance approaches and regulations should appropriately consider currently under-represented groups and focus on protecting vulnerable people, i.e., they should pay particular attention to the most vulnerable and the most affected. A particular role and weight should be given to them in any relevant decisions taken, also with regard to governance, design, and operation of converging technologies.

Ninth, further elements of an effective and acceptable international solution should be determined based on transparent, fact-based, public debates and forms of participatory decision-making that people find legitimate. To prevent abuse, future regulations should be inclusive, i.e. participatory and trustworthy, hence, transparent. Among others, this requires developers to explicitly list and label micro- and nano-scale components, to mention possible dual-uses and side effects, and to ensure a reasonable degree of explainability and amenability to both, ex ante and post hoc inspection for AI algorithms (Gunning et al., 2019). The goal must be to inform people adequately, comprehensively, and truthfully about the nature and amount of the data collected, as well as about the data governance and business models employed, and possible effects and side effects resulting from them.

A tenth, procedural challenge concerns the suitable institutional body responsible for deliberating on the afore-listed reforms and enacting them. Currently, none of the existing economic and political systems, institutions and frameworks appears to be well enough positioned and committed to handle the threats in a way that one could fully trust. However, trust is needed, because, if convergent technologies were misused, this would irreversibly damage trust in technological progress altogether. We would like to argue that, in the socio-technical systems of today, social, not just technical, innovation is needed for a suitable and effective governance framework. Without concurrent social and economic reforms, we will not be able to unleash the full potential of converging technologies – there would rather be the risk of backlash. Altogether, it appears to us that novel institutions and a new social contract are needed (See Table 2).

Conclusions and outlook

In summary, converging technologies inaugurate a new phase of socio-bio-technical innovation, one in which organisms and machines may converge and co-evolve into increasingly integrated cyberbiological systems. While the convergence of organisms and machines forecasts a future of enhanced human capabilities and wellbeing, it is overshadowed by significant ethical, legal, and existential challenges. Reflecting on these challenges, our paper calls for the development of a converging international governance framework and elucidated pathways for its realization.

Based on our analysis, we conclude that, to cultivate an effective governance ecosystem, we must first articulate general principles that reflect a global consensus on ethical norms, human rights, and sustainable development goals. Research institutions, along with interdisciplinary think tanks, can play a pivotal role in formulating these principles. They can provide the intellectual scaffolding, by synthesizing insights from diverse fields such as ethics, law, and technology studies. Governments, international organizations, and industry must then translate these principles into specific recommendations and regulations that are sensitive to cultural and contextual nuances.

Who should do this? In our view, this should encompass a broad coalition of stakeholders. Policymakers, technologists, ethicists, and civil society should collectively engage in this endeavor. In particular, technologists and innovators are called upon to adopt a 'responsibility by design' approach, ensuring that ethical considerations and values are embedded in the development process. Policymakers must ensure that regulations are adaptive and based on sound evidence, facilitating innovation, while protecting individual and public interests, and those of nature.

Where should this happen? We think, it should happen both, in national and international arenas. Nationally, governments should establish regulatory bodies and innovation hubs that foster the development of converging technologies, while assessing and mitigating risks. Internationally, many believe that existing bodies such as the United Nations, the World Economic Forum, and the WHO would be suitable platforms for dialogue, policy development, and coordination. This should have solved most of the CT-related problems by now, but it has not. Therefore, one should consider the establishment of a new specialized organization or consortium dedicated to converging technologies, which would be able to provide the focused leadership necessary to navigate this complex domain.

Moving forward, we suggest a multi-stakeholder approach that leverages existing frameworks and fosters new partnerships. Case studies of successful technology governance, such as the regulation of medical technologies, offer valuable lessons that can inform the governance of converging technologies. In parallel, the exploration of uncharted territories in technology policy should be encouraged, as they might reveal innovative governance strategies that are more attuned to the dynamism of technological convergence. In light of the vast landscape of converging technologies, it is clear that no single entity can shoulder the responsibility of governance alone. It is a shared journey that requires the collaboration of diverse actors across the globe. By engaging in a continuous discourse, setting clear milestones, and remaining vigilant to the evolving nature of technology, we can strive to guide the trajectory of technological convergence towards the most beneficial outcomes for individuals, society, and nature. By calling for the development of an international governance framework, we also call for the development of adaptive and evidence-based regulatory mechanisms to coordinate technology management regimes in the face of the complexity and uncertainty associated with technological convergence.

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Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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