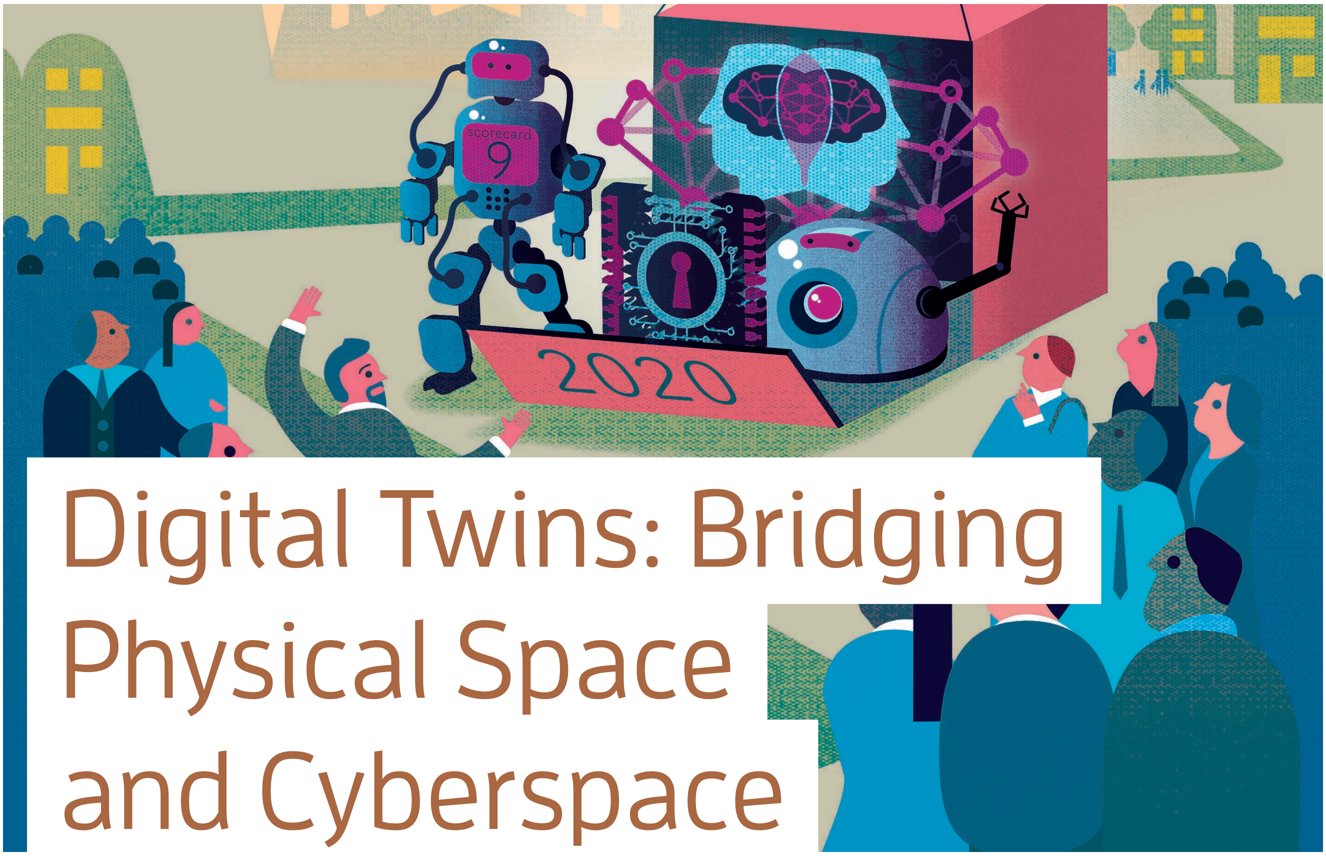

Digital Twins: Bridging Physical Space and Cyberspace

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A digital twin is a digital model of a real entity, the physical twin (such as an object, a process, or a complex aggregation). It is both a digital shadow reflecting the status/operation of its physical twin and a digital thread recording the evolution of the physical twin over time.

Digital twins are becoming a key component of the digital transformation, and they are sometimes an enabler of the digital transformation. Over the years, they have evolved, and they will keep evolving in the next decade. Market & Markets is foreseeing their market value to reach US$15.3 billion in 2023.[1]

A digital twin is a virtual representation of a physical entity that can be used during the design phase to foresee, simulate, and analyze behavior and keep a record of evolution (Figure 1). General Electric[2] has employed digital twins in its manufacturing processes and to in monitoring and managing equipment operations (such as wind farm turbines and aircraft engines) since 2013. The company estimates that digital twins help avoid US$1 billion in annual losses from its deployed assets.[3]

Mevea is using digital twins[4] to create a virtual model of a product (specialized backhoes) enabling its (virtual) operation by the end user during the specification phase. The company incorporates the models into production processes and uses the digital twins, enriched with manufacturing data, to monitor the backhoes' real-world operation to provide upstream information for engineering and assembly purposes and downstream data that help

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owners fine-tune the equipment and perform preventive maintenance.

PREDICTION

Digital models are based on CAD, and it is easy to understand why several industries have adopted them. Supply and manufacturing companies employ digital processes and digitally controlled machines to create digital threads; products are designed to connect through a communication grid and relay operational data used to produce digital shadows. Digital twins contribute to the value chain, and industries including architecture, engineering, construction, and health care[5] are starting to consider creating and exploiting them.[6]

The growing consensus is that, during the next decade, digital-twin applications will expand in many areas[1] and that the models' capabilities will improve. Let's consider two examples related to new fields of application, one in health care, where digital twins are beginning to include humans, and the other in education. We will then study an example of the extension of digital twins' capabilities.

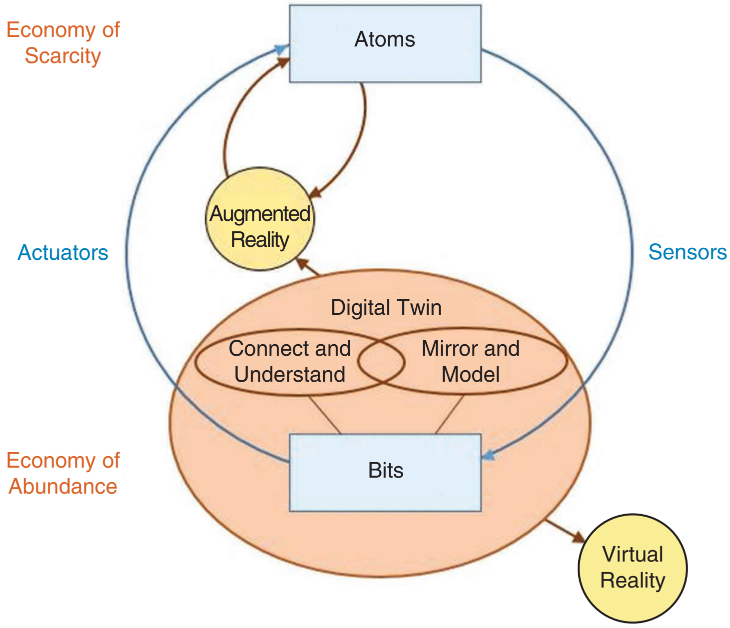

FIGURE 1. The digital transformation makes it possible to operate in cyberspace, decreasing processing and transaction costs. Digital twins create a bridge between the world of atoms and the world of bits.

Health Care

The health-care sector[7] is one of the most promising fields for the use of digital twins. General Electric has begun to use digital twins to simulate[8] and monitor hospital operations. However, during the next 10 years, it is likely that digital twins will be applied to people. As engineers leverage the growing amounts of available data, we can expect to have our own digital twins that monitor our health and simulate potential cures. Organs on chips[9] are already available to test the effectiveness of drugs. They are very complex systems in operational terms (harvesting cells, cultivating them, printing them to emulate an organ, and keeping them alive), and anything that could simplify the approach to a personalized remedy would be most welcome.

The sequencing of the genome is becoming more effective (faster and at a lower cost), so it is probable that, by the end of the next decade, every newborn will be genome sequenced, which would mark the starting point for creating human digital twins for health care. As babies grew, data (including medical exams and prescription-drug results) would be captured by ambient, body-worn, and, possibly, embedded sensors. The availability of millions of digital twins would make inference possible [that is, the application of artificial-intelligence (AI) algorithms] and help practitioners gain knowledge that could be used for proactive health care, which would become the future of medicine.

Education

Education faces a growing challenge: keeping pace with the explosion and obsolescence of knowledge. The former is making it difficult to even know what we don't know. The second demands continuous education to fight the loss of competence and appeal in a job market where employers are searching harder to find skilled professionals.

It is a challenge faced equally by individual professionals and companies. A few years ago, IBM, proposed the concept of a "cognitive digital twin"[10] applied to manufacturing (Figure 2). The idea was, and still is, to enrich a digital twin with cognitive capabilities, both internally and through cognitive-capable sensing. The notion that a digital twin could be a cognitive entity, hence

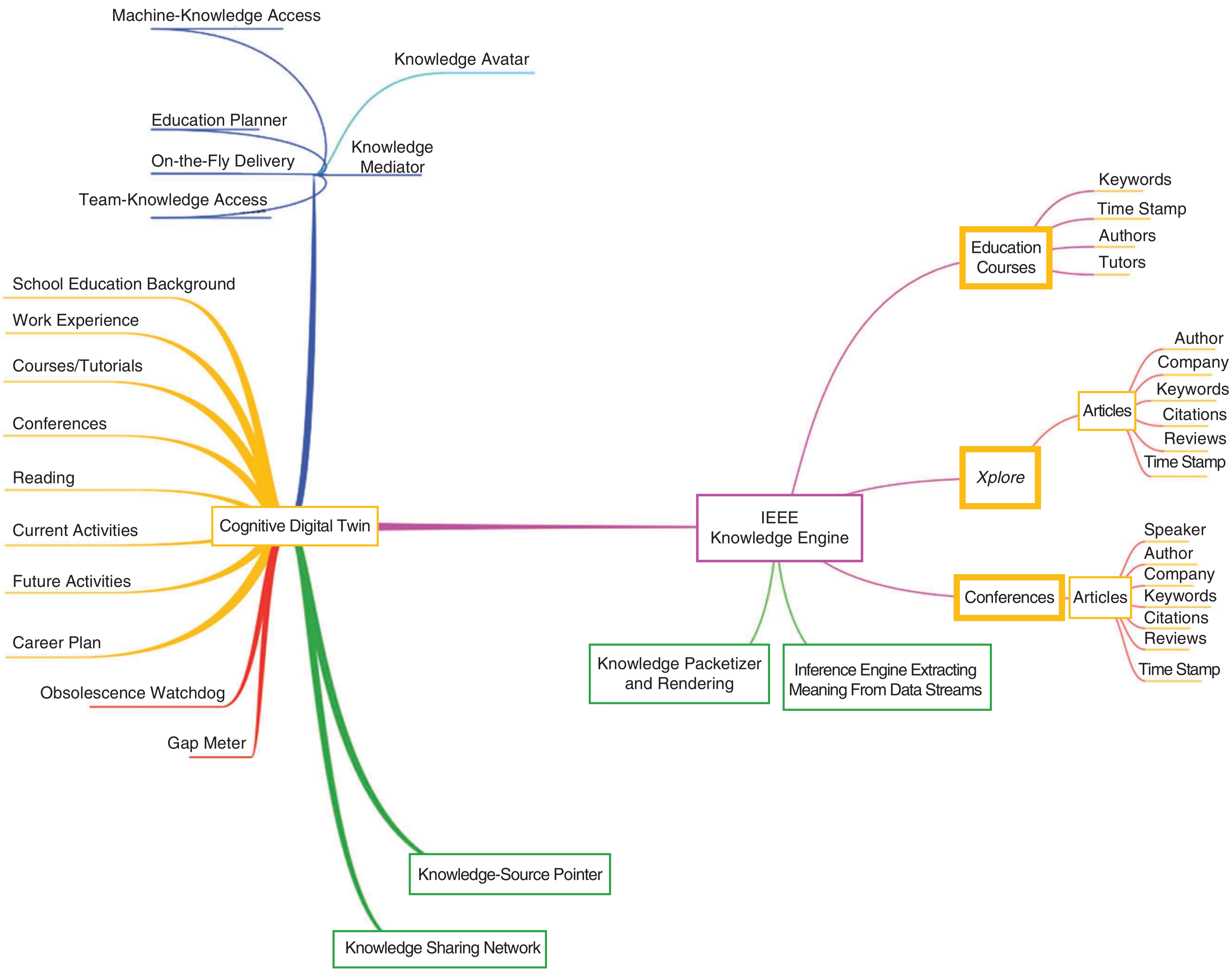

FIGURE 2. A schematic of a cognitive digital twin applied to professional education designed to leverage knowledge across the IEEE landscape, including *Xplore*, educational courses, and conferences. The cognitive digital twin is used by applications owned by an individual (to avoid privacy issues) to identify knowledge obsolescence and gaps (red branches). Other applications (blue lines) customize education delivery to maximize knowledge-transfer efficiency and support knowledge sharing (green lines), that is, pooling people and/or machine knowledge.

owning knowledge and able to exploit it (a database can store knowledge but can't exploit it; it doesn't "know" that it is storing knowledge) is an interesting one that could help to extend digital twins to the field of education.

This is one of the results coming out from the Symbiotic Autonomous Systems Initiative.[11] Given the significant number of interactions that each one of us has through electronic media and considering that many of those exchanges can be authenticated (that is, linked to us), it becomes possible to automatically infer the knowledge we have and understand how it evolves through time. Of course, a good starting point would be for each of us to opt in and provide information about our curricular educations, job experiences, and so forth, which can be easily shared through social networks (for example, Facebook and LinkedIn). Our attendance at conferences, the papers we have submitted, the papers and articles we have read, and our results in training courses all contribute to the shape of a personal digital twin that could be used to identify knowledge gaps and propose ways to fill them, customizing education to the specific way through which each of us learns most effectively (and, obviously, leveraging what we already know). The process can also consider a person's situational context (for example, location and activities), providing tailored education solutions that make learning more effective.

Digital twins were invented to mirror physical entities with a level of fidelity (accuracy) and synchronicity adequate for specific purposes. It is likely that digital twins (which are in stage 3) will evolve (stage 4) toward a super entity that they comprise with their overlapping physical counterparts in a symbiotic relationship, which would mirror another outcome envisioned by the Symbiotic Autonomous System Initiative. The super entity's characteristics would stem from both of the twins (which is not true in stage 3) and their symbiosis. For example, the digital twin could serve as an avatar that roamed cyberspace and (partly) represented the physical one. We already have an example with UBS[12] using the digital twin of its chief economist to speak with clients. Digital twins made of bits can be duplicated as often as needed and dramatically expand the superorganism's footprint.

Applications that flank digital twins can expand the models' characteristics. For example, applications can scan the digital thread (the digital twin's evolution through time) and derive some meaning. Imagine an application that knew what you had been doing during the past month and communicated with digital twins representing the people you had been in touch with. It might detect the first signs of a contagious disease and warn you to see your doctor. It could even provide the doctor with information about your associates and how they were reacting to prescribed cures. There is no limit to what an extended digital twin could do.

IMPACT

Digital twins are becoming an integral part of the digital transformation, any area of which could be affected by their application. They resulted from digitalizing the specification, design, and manufacturing processes, and they are kept alive by a pervasive communication fabric that connects them to the Internet of Things devices, with the outcome of converting products to services. That transformation presents a clear opportunity for companies to monetize their investments beyond product sales. At the same time, it generates data that lead to continuous improvements in manufacturing processes and goods (in subsequent releases), which is in line with the Industry 4.0 paradigm. The shift from products to services is bound to benefit the environment as well since it extends product lifetimes, reduces the quantities of the raw materials that are necessary to create replacement products, and lessens the amount of waste that must be recycled.

Digital twins that deliver additional capabilities (stage 4) will stimulate third parties to develop service-related features and will require an open framework for the engineering of (soft) add-ons and a certain degree of standardization. The latter could result from companies opening their product ecosystems as well as from devices that comply with certain platforms, as with the smartphone, where the platform is both the operating system (for example, Android and iOS) and the marketplace (for example, Google Play and iTunes).

The effectiveness of digital twins in manufacturing is prompting their adoption in other areas, such as health care and education, as previously mentioned. In both sectors, there is a shift from modeling objects and/or processes to copying people (digital twins are used to mimic facilities and complex medical devices, but here I am referring to patients). Modeling people is not new and does not necessarily involve digital twins. For example, pharmaceuticals companies digitally clone organs and, more recently, bodies (several organs) to study the effects of drugs as they search for new compounds and evaluate medicines' effectiveness for specific patients (cancer treatment is increasingly based on this). The use of digital twins to model people, however, is shifting the focus from atoms to bits. That provides several advantages (cost, speed, and so forth), but at the same time, it creates issues that I will discuss in the next section. We can say that the possibility of having digital twins flanking us could significantly impact our lives, relieving us of some burdens and improving our effectiveness in several areas.

TECHNOLOGY CHALLENGES

A digital twin is composed of a digital model, shadow, and thread. Each element has specific technology challenges. In addition, we shouldn't forget that, in the coming years, digital twins are bound to extend their capabilities (making use of technologies such as AI) and become a component of superorganisms: the symbiosis of the physical and digital twins. Both aspects of that evolution present difficulties.

Digital models

Depending on the application, there are different ways to create digital models, and this diversity is not helping the portability of models across different areas and, sometimes, within the same space. In most cases, there are no standards; rather, the modeling format is a consequence of the software supporting it (CAD), which is the result of vertical growth often driven by big companies imposing their processes and tools. There are areas, such as the modeling of a city, where different components (including power infrastructures, cadastral maps, telecommunication infrastructures, and so forth) are modeled in different, incompatible ways. That increases the cost of creating interoperable applications spanning several components. It would be desirable to work out a bottom-up approach to manage the situation. Another aspect is that digital models can be used by virtual and augmented reality applications that connect the digital and physical parts. Here again, the existence of interoperable models would boost application creation.

Digital shadows

Shadowing requires synchronization between the physical twin and its digital one. This, in turn, requires the physical twin to provide data mirroring its status at suitable, meaningful intervals, and a communication channel of some sort to transfer these data. Communication technology is becoming more pervasive (and affordable), and various paradigms to support it are being introduced (synchronous with low latency, synchronous with latency, asynchronous, direct, mediated, and so on). There is already a broad application of shadowing, from windmill turbines signaling their performance[13] to semi-autonomous cars reporting their condition once a day. Depending on where the physical twin operates, different communication infrastructures are used. Robots in a factory are most likely to employ Wi-Fi, while those operating in public spaces may rely on radio cell networks. At home, a person's digital twin may connect to a variety of ambient sensors (including smart mirrors and toilets) to harvest data.

Digital threads

All of the data received by the digital twin may be stored to keep track of the model's evolution. Most of the time the storage is in the cloud. However, in the case of a person's digital twin, there are proposals to encapsulate those data in a directly controlled device, such as a smartphone. We are just beginning with applications in this area, and there is no defined architecture for digital-thread data storage. Given the amazing progress in data storage, the retention issue does not seem to be critical, in terms of capacity, through the next decade. Privacy, availability, and ownership dominate the discussion and steer the solutions, a fact that may change during the longer term. Additionally, as digital twins move to stage 4, they will start to clone themselves and roam cyberspace, taking their data with them, so different architectures may be required. The synchronization of instances will become a major issue. Blockchain technology may also play a role in providing a certified digital thread.

Extended digital twins

An extended digital twin goes beyond the mirroring, shadowing, and threading of its physical counterpart. It becomes active and extends its equivalent's characteristics. In addition, it can take action on behalf of its physical counterpart, becoming an avatar (since it can be seen as impersonating its physical twin). That extension is a natural and logical step, but it distorts the very idea of a digital twin since, strictly speaking, the model is no longer a twin. However, if we move to stage 4, where features overlap between the physical and digital counterparts, we acknowledge the situation in which the digital twin complements the features of the physical one. In particular, the digital twin can leverage its bit-based form to duplicate itself without limitation. Hence, it can appear in many contexts at the same time, interacting with applications and interconnecting with an unlimited number of entities in cyberspace. Furthermore, applications may operate with the digital-twin data and produce additional features (for example, supplementary knowledge).

We are just starting the shift toward stage 4, and there is a lot that needs to be studied and worked out. In stage 4, digital counterparts will be open to data exchanges outside the twin–twin relationship, but, at the same time, they must preserve their identities and the association with their physical doubles. Whatever results from that openness (such as the acquisition of additional knowledge and experience), the digital twin has to find a way to synchronize with the physical one. Most of the time, information will not be transferred to the physical twin, but it will need to be present during exchanges between counterparts, and it will affect the interactions that the physical twin has with its environment. The other tricky issues to be addressed include accountability and ownership, and resolving them will require further study and research.

Superorganisms

At stage 4, there will be no more separation between the digital twin and its physical counterpart. Together they will create a superorganism. That transformation will have a significant impact in the industrial sector, and we can expect Industry 4.0 to leverage superorganisms throughout the value chain. The symbiosis between personal digital twins and their human counterparts could give rise to a trans-human species. Indeed, the symbiosis might result the first instance of trans-humanism. The technological issues mirror those regarding extended digital twins. Here, they become more crucial since, with superorganisms, the separation between digital and physical will fade.

UNCERTANTIES AND RISKS

That digital twins will continue to extend their footprint during the next decade is a given. The acceptance of personal digital twins and the uptake of cognitive digital counterparts are not certain. Much will depend on the services that personal digital and cognitive twins deliver. They raise concerns in terms of privacy, ownership, and accountability. A regulatory framework may be needed, but it could prove to be insufficient since a roaming digital twin might overstep boundaries and play in cyberspace domains that have different rules (or none at all). That is a general problem that goes well beyond digital twins, and as such, it will have to be managed at a higher level.

Another aspect that is particularly relevant to cognitive digital twins is the uptake of AI in data analytics (digital threads) and extended digital twins (machine learning). It connects to and complicates the issues that were previously mentioned, in particular those that relate to accountability. We have security risks that will become increasingly important as digital twins intertwine with the real world to the point of influencing and even becoming a part of it, but again, this issue is common to everything in cyberspace. A good indicator of how it will be faced, addressed, and solved will come with the use of digital twins in the health care.

Digital twins are a reality in several industries. They work so well and are so economically beneficial that their spread to other areas is certain. As they evolve and become more pervasive during the next decade, issues of ownership and accountability will have to be tackled. Additionally, human digitalization will begin in the health-care arena (we already see the first signs) and extend to other sectors, including education, and bring additional issues, such as privacy and the sense of self, to the forefront. As with any technology, security concerns are crucial, and a regulatory framework is necessary. ■

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