Digital Transformation
lights and shadows

We have been talking about Digital Transformation for decades. The growing pervasiveness of computers in all facets of life and business has made the world of bits a constant presence. This presence, in turn, has changed both our lives and business.

However, it is only in the last few years that the Digital Transformation moved from being an ongoing, unpiloted process to a target on its own for industry, business, and institutions [1].

It is even seen as a tool to accelerate a sustainability transition [2].

Quite often, the introduction of computers is considered as the Digital Transformation, but that is just a first, required step on the path leading to it, as shown in Figure 1.

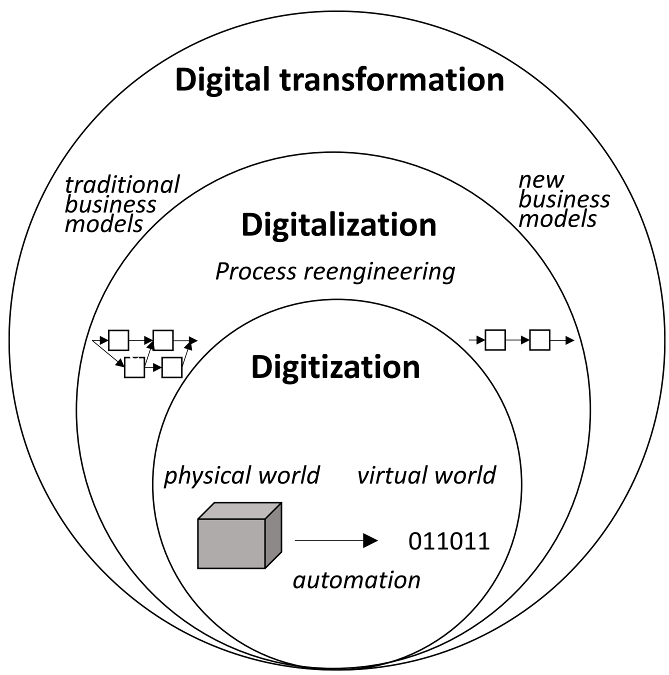

Figure 1. The three steps towards Digital Transformation

The next step is Digitalization. Digitalization involves the re-engineering of processes to take advantage of the digital world. The end step of a Digital Transformation takes place when the business takes advantage of the new resources (data) made available by the previous two steps.

In this sense, the Digital Transformation is not about computers, but rather about re-inventing the way of doing business and the business itself.

Typically, the evolution towards a Digital Transformation is driven by the continuous effort of enterprises to increase their efficiency, for example by reducing cost, both internally and throughout the value chain [3]. However, in any competitive system, the reduction of production costs leads to a decrease in price to the end customer, leading to decreased margins to the producer. This is a paradox: the industry invests money to grow more efficiently but the advantage goes to the end customer. At the same time, in any competitive system there is really no alternative: if you are not efficient you will be ousted from the market.

The goals of a Digital Transformation can and should go beyond just increasing efficiency. It should offer the possibility to widen the product portfolio, reshape the business, and generate new revenue streams.

To understand this, let us look at the underpinning of any Digital Transformation, shown in Figure 2.

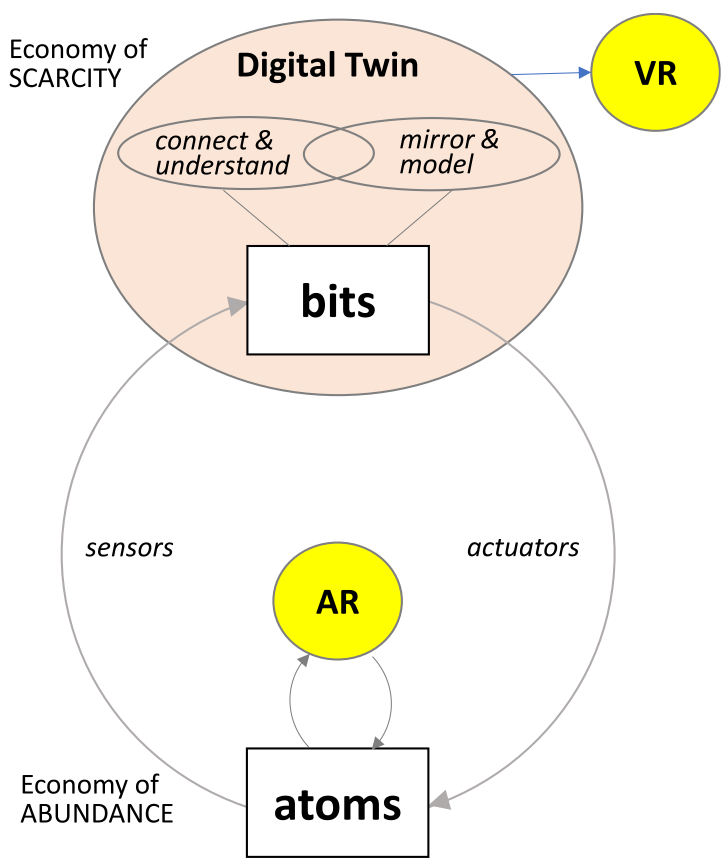

Figure 2. The underpinning of the Digital Transformation

We live in a physical world represented by atoms while the virtual world is represented by bits. Over the past 50 years, the availability of sensors has enabled the mirroring of atoms into bits, that is, representing the characteristics of a physical object using a digital model. This mirroring proceeded along with advances in computer technology that allow the generation, manipulation, and visualization of these bits. The vast majority of physical systems can now be simulated or emulated in the digital space. For example, think about the design of a car: It used to require the creation of a wooden mockup, followed by prototypes, the verification of compatibility among the thousands of components (produced by hundreds of companies), and finally arriving at the blueprint of the car. Then, it was a matter of designing the assembly line, organizing the robots and finely tuning the whole. This process took significant time and resources. Now, all of this can take place in the digital space. Once the car has been designed and simulation has proved its viability, the organization of the assembly line also takes place in the digital space. Technologies like Virtual Reality (VR in Figure 2) allow designers to plan and test solutions in cooperation with suppliers. Once the design of both the product and the production line is complete, the digital model is used for execution: robots are programmed (mostly autonomously), supply chain processes are put in place, workers are trained on the new product assembly, and so on. This is shown in the figure with the lines of actuators between bits and atoms.

Notice also the increasing use of AR (augmented reality) to help bring the digital world onto the physical world and close the gaps between the two. This practice is starting to be known as the “industrial metaverse” and goes along with the operation using virtual reality (VR).

The simulation of complex systems has evolved towards the use of digital twins [4], as shown in Figure 2. A digital twin is a virtual model designed to accurately reflect a physical object and goes beyond simply simulating its physics. For example, artificial intelligence (AI) and machine learning (ML) are key technologies that help making sense of the data collected by sensors and turn that data into a more accurate digital twin with more advanced capabilities. While the previous generation of simulators was using first principles to build virtual model of simpler subsystem, the Digital Transformation has created a data explosion that makes AI indispensable to extract the insights and synthesize them into digital twins.

For example, in the IoT world, platforms like Mindsphere [5] (by Siemens), take care of the entire life cycle, from design to supply chain, from manufacturing to delivery, from sales to operation. Effort is now underway to extend life-cycle management to include product end-of-life (decommissioning, recycling, reuse of parts, etc.).

Let’s take a closer look at the role of digital twins in the Digital Transformation of Manufacturing. The Digital Transformation generates efficiency in the system and this efficiency impacts both the bottom line of companies and the resources they use. As noted, expanding the portfolio and re-thinking the business is imperative. Some of these resources will no longer be needed, which affects workers both inside the company and in the value chain and ecosystem, and new resources will be needed, including new skills and their acquisition.

Since the Digital Transformation has broad impact affecting the value chain, the ecosystems and the end users, companies may have a difficult time engaging in the transformation since they do not control the entire chain. Big companies can “force” their environment to change along with them, but smaller ones may have to adjust to an unsynchronized environment. This issue is particularly relevant to governments and institutions that need to consider the whole landscape in order to find an effective way to foster the Digital Transformation.

Let's consider some of these aspects, starting with data---the raw resources used and produced by the Digital Transformation---and continuing to digital twins and their use to foster and support the Digital Transformation. We will then explore examples in different sectors and conclude with some thoughts on how the Digital Transformation can be addressed by industry, governments, academia, and the IEEE.

As with all technology-fostered transformation, Digital Transformation delivers some very good benefits to business and society but at the same time, casts some shadows in the process and in the outcome. In this article, we try to outline both the lights and the shadows in the belief that by knowing them, we can leverage the former and minimize the latter.

Leveraging Data

We are drowning in data to the point that the real challenge is identifying the data you need and understanding what it means. The Digital Transformation, as noted, exacerbates this challenge because data is, as a matter of fact, the starting point for any Digital Transformation. Data analytics is already used in many industries to make sense of data. As shown in Figure 3, data can be collected from different sources and data analytics can extract meaning from these sets of data. The data and their meaning in turn can be leveraged in the industry processes steering them. The next step, characteristic of a full-blown Digital Transformation, is the exploitation of data to create new services, and expanding the offered portfolio. As shown in Figure 3, the Digital Transformation aggregates data, as a starting point, and then generates new data that will be used to make processes more efficient and to expand the business opportunities. Data will continue to flow in, from the internal and external processes, as well as from the end users. Again, what matters most is the capability to identify relevance and extract meaning. As people say "data is the new currency" of the digital age.

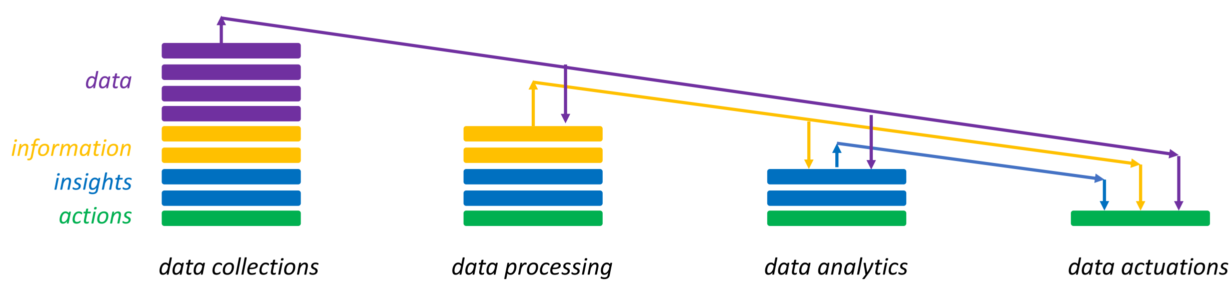

Figure 3. The increasing value of data as Digital Transformation is applied

In Figure 4, we show the increasing value of data as it moves from "raw" data to actionable entities. The data provided by sensors mirrors the current (or past) status of the physical world. Data analytics is the tool to understand the current situation, also known as *descriptive analytics*.

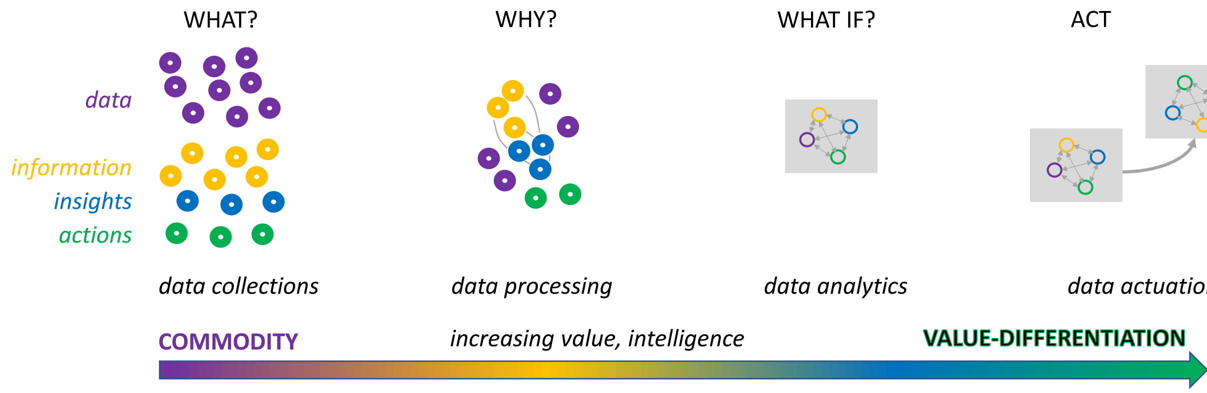

Figure 4. Moving from understanding of the current situation to influence its evolution

By injecting intelligence (like looking at past situations and their evolution over time) and correlating other streams of data, it may be possible to understand the underlying processes, also known as *diagnostic analytics*. Although this may be useful, it is still in the realm of commodity. The next step, taking us into the "added value" domain, is to simulate what could happen next (is the situation going to get worse? will it resolve by itself?). This is known as *predictive analytics*. The value is evident since accurate predictions allow taking countermeasures for the predicted changes. This also leads to the last step in leveraging data value, through *prescriptive analytics*. Here the system, either automatically or via human actors, takes action to make sure that the current situation evolves along the desired lines.

The further we move up this ladder of data analytics, the more value can be generated, but also the more complex the overall situation becomes.

To start with, not all data being used may be "owned" by the entities using them. For example, a company may provide additional service on a product to a specific client by monitoring the way it is being used, the context in which it is used, etc. There should be transparency on what data is harvested, how it is used, and on the mechanism applied to derive meaning, and take actionable decisions.

The European Union has taken steps with the GDPR [6] regulation (General Data Protection) to identify the rights of use and the ownership of data, but the situation in the real world can become muddy and difficult to sort out. As AI is thrown into the mix, the picture becomes even fuzzier and the EU AI Act [7]---although representing a good attempt at regulating the use of AI---may fall short in some situations. The problem is that, in general, there is a trade-off between what is useful (to a company, to an end user, to society) and the preservation of the personal sphere and an individual's right to control how their data is used and by whom.

In industry, the focus on effectiveness, smooth operation of the value chain, flexibility, and sustainability is driving a search for solutions where data can be shared in an effective but controlled way. This is a crucial point in implementing the Digital Transformation across the industrial value chain and ecosystem. That is the aim of several initiatives worldwide. For example, the Gaia-X [8] initiative launched by the EU, currently with the participation of over 850 companies worldwide, is a decentralized and federated data platform aiming to create a common standard centered around openness, transparency, and trust. The most significant results of Gaia-X so far have been achieved in the automotive sectors, through the definition of data spaces for the automotive industry to support the Digital Transformation of the whole sector, both to increase efficiency and to enable the offer of new services.

Digital Twins

If data is the raw resources to build the Digital Transformation (as well as one of the outputs of the Digital Transformation), digital twins are crucial tools and components of the Digital Transformation [9], as shown in Figure 2.

A digital twin is a virtual model of a product, component, equipment in the production line, a process, a company, or even an entire complex ecosystem, like the ocean (or, to the extreme, the entire earth). In a nutshell, a digital twin is an actionable virtual counterpart of a physical system present in the physical world.

Its adoption in the industrial world has been quick, fostered by the presence of supporting platforms for the manufacturing industry that rely on digital twins. At the same time, the pervasive presence of IoT sensors in products and the growing penetration of the communication infrastructure have connected the end user (that is, the end product being used) to the manufacturing value chain. This connection in turn enables new, as-a-service delivery, which extends the product portfolio and generates additional revenue streams.

Figure 5 shows the recent evolution of digital twin usage in design and manufacturing. It starts in the design phase, representing a future product. It continues to coexist with the actual product for simulation purposes. It culminates in stage 3, the most common usage in industry nowadays, where the digital twin is connected to its physical entity.

Some applications of digital twins are already seeing its evolution to stage 4 where the digital twin provides some of the features perceived by the end user, in a way augmenting the physical entity. The expected evolution in the near future is towards a growing autonomy, stage 5, where the digital twin acts independently of the physical entity to operate in cyberspace. This is a further step towards yet a higher level of Digital Transformation.

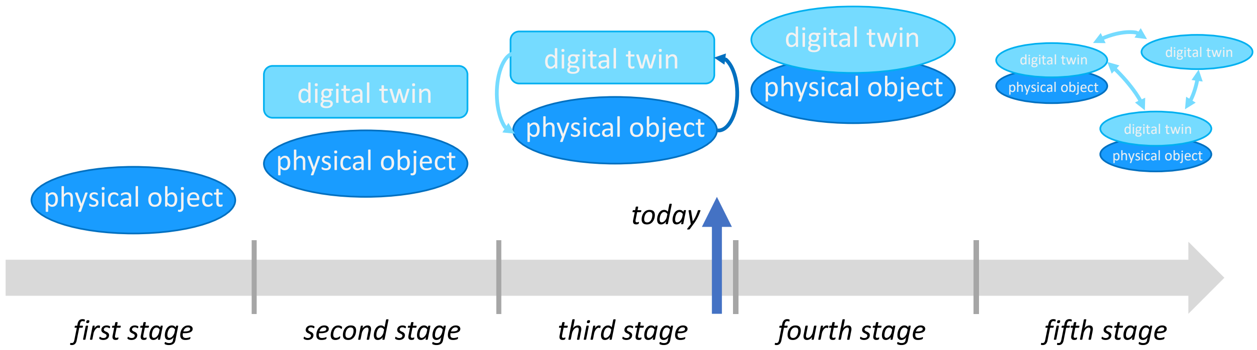

Figure 5. Digital Twin evolution

Digital Transformation in a Few Sectors

Manufacturing

The starting point for manufacturing is the use of computer-aided design (CAD)-generated data. CAD tools create a standardized digital representation of the product that can be used as the digital model of the product digital twin. For example, Mindsphere (by Siemens) has been one of the pioneer tools and enablers. Software companies like Mevea have expanded their digital twin products to address the entire product life cycle. End users like Boeing, GE and Tesla have been first adopters of the digital twin trend.

Construction

The starting point in the construction sector is using the Building Information Modelling (BIM) tool that generates (like the CAD for industry) the digital model of the construction (building, bridge, mall, etc.). Companies like ARUP and GE have rapidly embraced digital twins, and even public entities (such as the government of Singapore) have started ambitious projects with the objective to model and automate several aspects of the whole city operations.

Healthcare

The healthcare sector can be seen as comprising the healthcare infrastructure (hospitals, equipment, drugs, prosthetics, etc.), related processes, and the patient. For the former, the starting point for data accrual, and generation of the digital models, is a combination of CAD and BIM, for the latter [10], the cornerstone is the EHR – Electronic Health Record. In this space companies like GE, Philips and Q.Bio have been first movers and developers of the technology [11].

Education

The education sector is possibly the most reliant on digital content. However, it is probably also the least advanced in leveraging that digital content. Most education "processes" and approaches are the same as they were when students used paper books and went to the library to get insights. The pandemic has surely increased remote teaching, but here again we are seeing a stretching of the classroom mediated by technology, not a different approach to teaching.

Possibly, the highest pressure to look for a new approach to education, and to execute its Digital Transformation, is coming from industry that is pressing for new approaches to continuous education, flanking and integrating education in everyday working activities. The use of VR and AR technologies can change education, if they go hand in hand with a change of the education paradigm.

Another force in education change and a component in the Digital Transformation of education is the integration of AI in the knowledge acquisition and even more crucially in the creation and access to executable knowledge.

The starting point in education to leverage the data is the creation of an ontology. An important tool to leverage it is the cognitive digital twin that customizes knowledge to a specific context and a specific user on one hand and on the other hand becomes the tool for sharing knowledge in a distributed knowledge network. A cognitive digital twin can be associated to a robot [12], to a person [13], to a company, or to an organization [14].

Antithesis, Playing Devil’s Advocate

The thesis of this article is that there is (or needs to be) a digital transformation across all sectors of life, business etc. This is a noble, laudable goal. But it may never happen, at least not everywhere and at all scales. There are many reasons for this.

Digital transformations do not represent a new paradigm. Data has been collected and used in various ways by humans for thousands of years. As the computational technologies improved, (e.g., from the abacus, to the slide rule, and to analog and digital computers), and sensor technologies improved, so did the ability to collect data, analyze it, and use it to make decisions and control the environment. The capability described here is just more powerful and pervasive today – but these aspects are all relative. True scientific revolutions come about only once every several hundred years (see [15]) it is hard to argue that increasing use and integration of existing technologies is anything but evolutionary, as opposed to revolutionary.

Challenges and Threats

There are many challenges and threats to achieving digital transformation at any scale. In the rest of this section, we discuss some of them.

Understanding and acceptance -- not everyone will understand and be able to fully use the capabilities of a digitally transformed environment. Does this lack of universal understanding and acceptance by some individuals exacerbate the digital divide? Even if the digital transformation is invisible to most users, digital divides may occur and objections may be raised by unwilling participants.

Technical challenges – these are well known (data deluge, privacy, networking, etc.) and discussed in many other places [16].

Resource challenges – sufficient materials (chips, batteries, etc.) to build out all of the devices and systems needed. At grand scale there are insufficient resources on the planet to provide equitable distribution of the technology.

Awareness – in a full Digital Transformation, not everyone will know or be aware of its existence, of the collection of their data, etc.– is this ethical?

Affordability -- Not every entity, state, jurisdiction, individual will be able to afford all of that is offered by the digital divide. These costs are described further below.

Capability to be digitally transformed -- Not everyone will be able to avail themselves to a full digital transformation – there will always be remote, underdeveloped, underpowered, under networked areas. Individuals require a certain level of education and sophistication – even with passive and "invisible" devices to interact safely with their environment.

Willingness and inclusion -- not everyone will want to participate in a full or even partial digital transformation based on privacy concerns, religious objections and lifestyle choices. Many people, even highly educated ones, fear or distrust sophisticated technologies.

Errors and mitigations – smart devices make errors. Data analytics produce erroneous results. Anyone with a home assistant is aware of the many mistakes and misunderstandings it makes. Even if the error rates are reduced to a tiny number a significant public risk is created. Connect these smart devices with consumer goods, infrastructure, automobiles, health devices and more at scale and we can expect a significant number of Digital-Transformation induced injuries, deaths and even catastrophes.

Digital Transformation at scale

Digital Transformation can happen at different scales. At the largest scale, global Digital Transformation is what is called for in the first part of this paper. Regional/State level addresses an entire country, even a small one that can be completely (or almost so) digitally transformed. Any major city, such as New York, Hong Kong or Paris could be fully digitally transformed everywhere, even in the "underbelly" of the city. Small city/ town – a complete or nearly complete digital transformation is more likely to happen in a small town.

Section –districts or blocks of a town or city could also be digitally transformed as a unit. At least in this case beta deployments can occur for debugging and analysis before deploying at greater scale. Village – perhaps at this level a digital transformation makes the most sense especially in the 3rd or 4th world. Home –a motivated individual could participate in a digital transformation exercise. But this requires time, know-how and financing. Not everyone will have all three.

In most cases the starting point of a Digital Transformation is within a single company, organization, or institution and then it propagates to involve interacting partners, both in the value chain and in the ecosystem. The local execution of Digital Transformation by a company, if successful, is likely to induce other companies to follow suit, to be able to interact with the changed context and or to be able to compete.

The order in which these transformations can take place is also important. It is likely that early successes in smaller environments (rural and home) could occur before those in large cities. However, there is a danger that the analytical data gathered at one scale will incorrectly bias those at a different scale. For example, water usage per capita in rural communities versus in metropolitan areas.

Costs of Digital Transformation

Any Digital Transformation costs significantly. At large scale (global, regional major city), it requires significant public funding. At smaller scales, it requires substantial local and individual funding. In all cases, technical expertise is required along with a willingness to fail during early stages of deployment.

It should be noted that one of the major costs of Digital Transformation is actually induced on the market: because of the lower transaction cost and increased efficiency, the price of products and services to the end customer is bound to decrease and the overall market value is going to shrink. In most cases companies embrace the Digital Transformation to grow more efficient, however, the business success of the transformation should be measured in the capability to increase revenue streams by expanding the offer portfolio and re-using the resources being freed.

The privacy costs have also been mentioned. Collecting all this data is intrusive and needs explicit permission and awareness. At greater scale, not everyone will want to cooperate – potentially introducing biases which may create under-represented categories, that are likely to exacerbate the digital divide. Even with near-total cooperation of a citizenry, there will be biases based on algorithmic deficiencies. Most individuals will not know about all of their data that is being collected or how it will be used. The societal costs of biased or erroneous algorithms could be high.

Summary and Recommendations

The role of academic research in advancing Digital Transformation technology is self-evident. Less evident is the substantial role academia can have in understanding and shaping the effects of this transformation on humanity, which in turn feeds into recommendations for policy makers and professional organizations.

“The care of human life and happiness, and not their destruction, is the first and only object of good government.” (Thomas Jefferson). To this end, regulators should aim to balance innovation and the welfare of humans. As technology and regulation increasingly mirror our lives in the digital world, they must do so while carefully protecting individual liberties and privacy.

More specifically, we make the following recommendations with regard to effective and meaningful digital transformation that can benefit humanity while making a business case.

Recommendations to Industry

- Increase transparency and openness of Digital Transformation processes for other players to participate.
- Abide by open-data harvesting policies and make it transparent and easy to customers to understand.
- Establish digital markets where all players can offer their Digital Transformation products and services and where consumers, industries and governments can acquire them.

Recommendations to Governments

- Introduce practical regulations on Digital Transformation and data usage.
- Introduce meaningful and effective incentives to follow regulations and policies, based on balanced combinations of enforcement and incentives.
- Coordinate international, cross-border regulations.
- Define and regulate the use of AI, without imposing an unrealistic burden that stifles innovation and progress.

Recommendations to Academia

- Innovate in terms of practical processes, policies and regulations.
- Model and simulate large scale digital twins, increase the use of data-driven AI to augment the functionality and improve the accuracy.
- Explore extreme requirements, such as real-time, reliability, acting in space, etc.
- Explore humans in the loop for AI and digital twins.

Recommendations to Professional Organizations, such as IEEE

- Define standards and best practices, gathering support from the various stakeholders.
- Recommend roadmaps for the adoption of Digital Transformation.
- Convene other three players: industry, governments, and academia to innovate and advance digital transformation.

Together or individually, these recommendations can help make Digital Transformation more effective.

This article is based on the work of IEEE Future Directions’ Industry Advisory Board that identified the Digital Transformation as one of the only three megatrends in these coming years. Metaverse (Virtual Worlds) and Sustainability predates this paper. Overall comparison of all three Megatrends will be the final article of the second year of Predictions Column.

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