What Will 2022 Look Like? The *IEEE CS 2022 Report*

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Over the last two years, nine IEEE Computer Society tech leaders collaborated to identify important industry advances that promise to change the world by 2022. The 23 technologies provide new insights into the emergence of "seamless intelligence."

American baseball personality Yogi Berra famously opined, "It's tough to make predictions, especially about the future." Forecasting is even more difficult in the computer industry, due to dramatic and swift changes in technology and the numerous challenges to innovation. Only a small fraction of innovations truly disrupt the state of the art.[1] Some innovations are not practical or cost-effective, some are ahead of their time, and some simply don't address a market need. Examples abound of arguably superior technologies that never achieved wide adoption—Apple's Newton, IBM's OS/2,[2] and Sony's Betamax[3] come to mind—because others arrived on time or fared better in the market.

OUR CHALLENGE

Despite Berra's admonition, in January 2013 Dejan Milojicic, then president of the IEEE Computer Society (CS), presented a team of scientists and engineers with the following challenge:

- predict future technologies that will disrupt the state of the art,
- help researchers understand the future impact of these disruptive technologies,
- help laymen understand where technology is evolving and the implications for society, and
- help the IEEE Computer Society organize and prepare for this future.

After two face-to-face workshops, followed by several months of email discussions and consultations with other technologists, we identified 23 disruptive technology areas and shared the list with the IEEE CS Industrial Advisory Board. We organized these areas around themes including market categories, technologies, human capital, and policies, as Figure 1 illustrates.

The 23 technology areas are

- life sciences;
- computational biology and bioinformatics;
- medical robotics;

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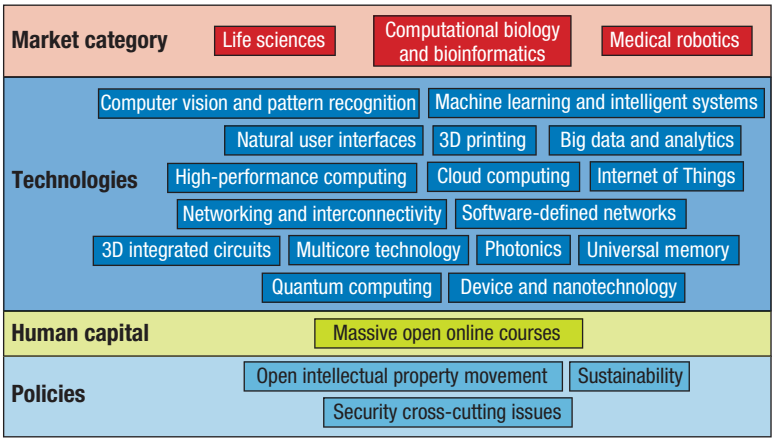

FIGURE 1. Landscape of the 23 disruptive technology areas. These technology areas are organized around themes comprising market categories, technologies, human capital, and policies.

- computer vision and pattern recognition;
- machine learning and intelligent systems;
- natural user interfaces;
- 3D printing;
- big data and analytics;
- high-performance computing;
- cloud computing;
- the Internet of Things (IoT);
- networking and interconnectivity;
- software-defined networks;
- 3D integrated circuits;
- multicore technology;
- photonics;
- universal, nonvolatile memory;
- quantum computing;
- device and nanotechnology;
- massive open online courses (MOOCs);
- open intellectual property movement;
- sustainability; and
- security cross-cutting issues.

We used this information to create the comprehensive *IEEE CS 2022 Report*, which describes each of the 23 technology areas and summarizes the state of the art, potential challenges, where we think each technology will go, and its potential for disruption. Some are already being adopted today, such as multicore technology, high-performance computing, cloud computing, and software-defined networks. Others are only being explored at this time, such as 3D printing, nonvolatile memory technologies, and quantum computing. The full report is available on the IEEE CS website (www.computer.org/cms/Computer.org/ComputingNow/2022Report.pdf).

In identifying these 23 technology areas, we hope to better align the CS with the industry and its professionals. We recognize that our list is incomplete and that several other technology areas, such as electronic currency and autonomous vehicles, may be considered transformational. But we had to draw a line. We also avoided the philosophical notion of technology's contributions to humankind, a question frequently asked by those who have read the report. The report's premise, echoed in this article, is that technology enables capabilities; what humanity chooses to do with that technology is beyond the report's scope.

DRIVERS AND DISRUPTORS

To validate the premises and conclusions made by the *CS 2022 Report* team, we surveyed more than 5,000 IEEE CS senior members. We posed related questions, but didn't share the report itself to avoid influencing members' responses. We received 690 complete survey responses and 368 partial ones. Of the total 1,058 responses, 784 were usable, yielding a response rate of 18.3 percent with a margin of error of ±3.2; thus, we could be 95 percent confident that the true answer lies within ±3.2 percentage points of the finding.

Kim Bartel Sheehan found in 2006 that the response rate for email surveys is inversely proportional to survey length and that response rates for email surveys have generally been declining, with an average response of about 31 percent.[4] So our response rate of about 20 percent seems low, but is likely due to this continued downward trend of response rates and the length of the paper we asked members to read, as it was more than 160 pages long.

Respondents' reported job roles were diverse, including engineers (44.97 percent), academics (11.69 percent), scientists (7.25 percent), researchers (6.95 percent), managers (5.77 percent), consultants (5.62 percent), and others (17.75 percent) including technologists and programmers.

The survey comprised two classes of questions, asking respondents to numerically rank our consolidated lists of *driver* and *disruptor* technologies. For instance, a rank of 1 meant the technology is not considered a driver or disrupter, 3 meant it's a moderate driver or disrupter, and 5 meant it's considered a major driver or disrupter.

For the drivers, we asked responders to rank the following items:

- increasing average life expectancy,
- increasing ratio of retirees to workers,
- public concern about control over access to and amount of personal information,
- desire for sustainable energy sources,

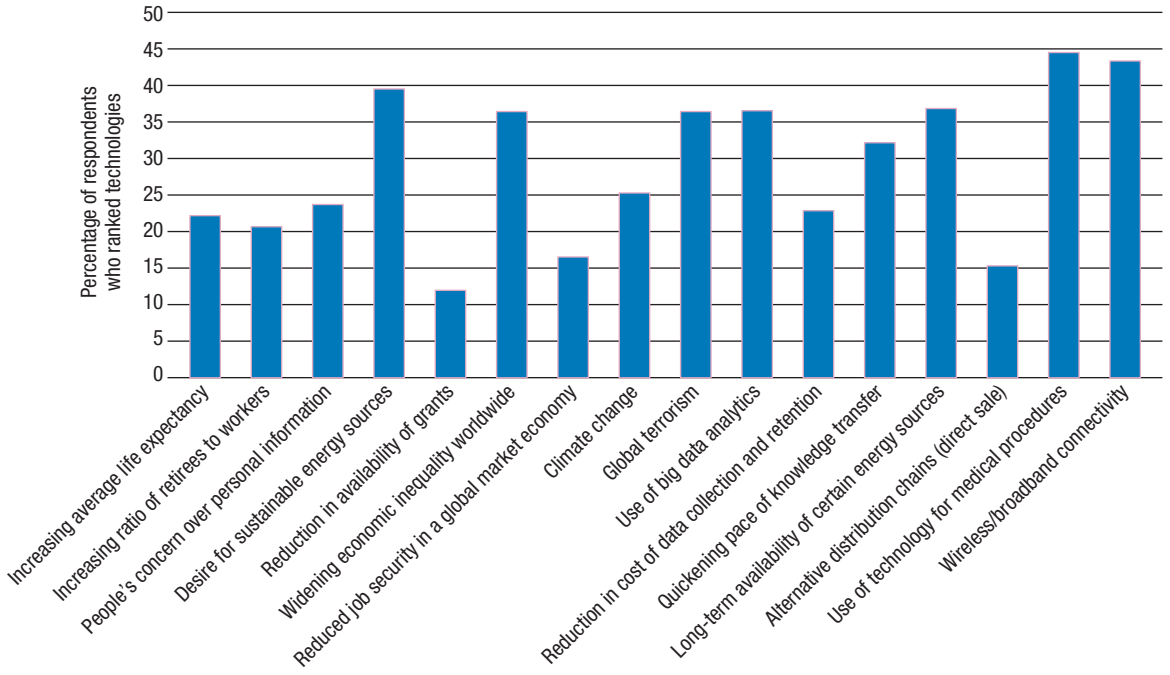

FIGURE 2. Comparison of major technology drivers as ranked by survey respondents.

- reduction in availability of grants and philanthropic resources,
- widening economic inequality worldwide,
- reduced job security in a global market economy,
- climate change,
- global terrorism,
- use of big data and analytics,
- reduction in cost of data collection and retention (for use in analytics),
- quickening pace of knowledge transfer such as instantaneous global communication,
- long-term availability of certain energy sources,
- alternative distribution chains such as manufacturers selling directly to consumers,
- use of technology for medical procedures, and
- wireless/broadband connectivity.

Figure 2 shows the percentages of respondents who believed that individual technologies are indeed technology drivers, which aligns well with the *CS 2022 Report* findings. For example, the highest ranked drivers were technology used for medical procedures, followed by wireless/broadband connectivity and the desire for sustainable energy sources. Also highly ranked were the use of big data and analytics, long-term availability of energy resources, and the quickening pace of knowledge transfer. All of these drivers are discussed in the report.

For the disruptors, we asked the responders to numerically rank the following:

- crowdsourcing/open sourcing of hardware development;
- changes in educational structure/design such as MOOCs;
- virtual/alternative currencies such as Bitcoin;
- smartphone use as a device for payment;
- cloud computing;
- use of robots as a source of labor;
- nonvolatile memory influencing big-data accessibility and portability;
- quantum/nondeterministic computing;
- 3D printing;
- green computing; and
- new user interfaces such as voice or motion instead of traditional keyboards.

Figure 3 shows the percentage of responders who believed that individual technologies are disrupters. Again, these results supported our findings in the *CS 2022 Report*; for example, the highest-ranked disrupters were the use of robots as labor and 3D printing, followed by cloud computing, MOOCs, and new user interfaces. The higher percentage of responses identifying drivers, compared to disruptors, supports the idea that only a fraction of technologies truly become disruptive.

SEAMLESS INTELLIGENCE

In creating the *CS 2022 Report*, we were searching for a meta-innovation that would tie all these technology areas together. We found a unifying theme in *seamless intelligence*, where everything is connected through ubiquitous networks, interfaces, and so on. While similar to previous pervasive and ubiquitous computing scenarios, seamless intelligence has deep roots in technology advancement that didn't exist in the near past.

Since the inception of digital computing in the mid-1940s, society has experienced a revolution in the acquisition, processing, and communication

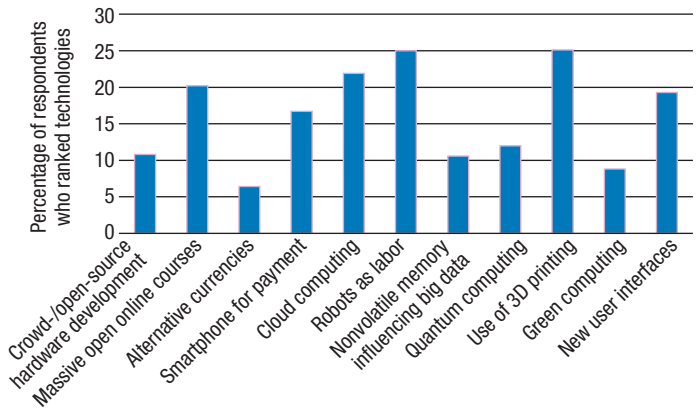

FIGURE 3. Comparison of major technology disruptors as ranked by survey respondents.

of information. This revolution has transformed every aspect of society through increased automation, ubiquitous access to information, and pervasive human networking. We continue to witness an increase in the number, shapes, and sizes of computing devices, as well as a combinatorial increase in local and global connectivity. With pervasive computing and communication capabilities, information technology will increasingly enhance and augment human knowledge, intelligence, and connectivity. We project that by 2022 society will advance so that intelligence becomes seamless and ubiquitous for those who can afford and use state-of-the-art information technology.

We expect this new reality to result from the confluence of multiple information and communication technologies. Computing devices—ranging from wearables, subdermal chips, and the computers inside our mobile devices, laptops, desktops, home servers, TV sets, and refrigerators to the computing cloud we reach via the Internet—will interconnect via different communication and networking technologies. Together, these will form an intelligent mesh: a computing and communication ecosystem that augments reality with information and intelligence gathered from our fingertips, eyes, ears, noses, and brain waves. See Figure 4 for a visual interpretation of this seamless integration.

The figure represents only a small fraction of the potential relationships, such as core computation and communication technologies influencing natural user interfaces and forms of recognition. Central to the figure, and to all technology, is information; core technologies build out in quasi-concentric rings to transform, in the outermost circle, both traditional and new vertical markets, including transportation, healthcare, agriculture, digital currency, and so on.

TECHNOLOGICAL GAPS AND CHALLENGES

Not all potential futures are certain or positive. Here we discuss some of the threats to the validity of our predictions and some of the ways that the enabling technologies could create new problems for future generations to address.

Seamless networking

At the heart of this new seamless intelligence integration is *seamless networking*, with transitions from one network device to another occurring transparently and without interruption. Various wireless networking technologies—from near-field communication (NFC) and Bluetooth to Wi-Fi and 5G networks—are already integrated with high-speed wired networking and the Internet, allowing anywhere-to-anywhere access. But we haven't yet reached true seamless integration.

To achieve seamlessness and realize logical end-to-end connectivity, communications will need to be able to run independently on top of any physical networking, regardless of device or location. Through virtualized end-to-end connectivity, we can achieve total integration of all ecosystem devices catering to specific needs. This new world will require sophisticated, intelligent coordination software. Voice, image, and motion recognition will transform human–computer interfaces into a seamless interaction between the user and all the computing devices in his or her life.

Identity federation

Another gap between today and 2022 is seamless reliance on federated identity and the use of more sophisticated identity technologies. Access will be authorized based on capabilities and access tokens rather than strictly on identity. Private applications will still require strict identity; for example, discovering via a social networking site that a friend happens to be at the same café as the user will require notifying peers about their mutual presence. But it will also require new ways to protect users from unwarranted identification.

To achieve interoperability, identity federation will require standards developed and agreed upon by identity providers. In addition, meta-identity information will play a major role, capturing a user's profile and managing his or her preferences while the user is shopping, eating, and traveling (for example, a hotel could detect a guest's preferred type of bed, floor level, or smoking status and automatically fulfill a reservation accordingly).

Intelligent software

Cloud services that offer APIs to facilitate application mashups will evolve into intelligent software able to integrate multiple services and achieve results difficult to imagine today. Current technology for overlaying location

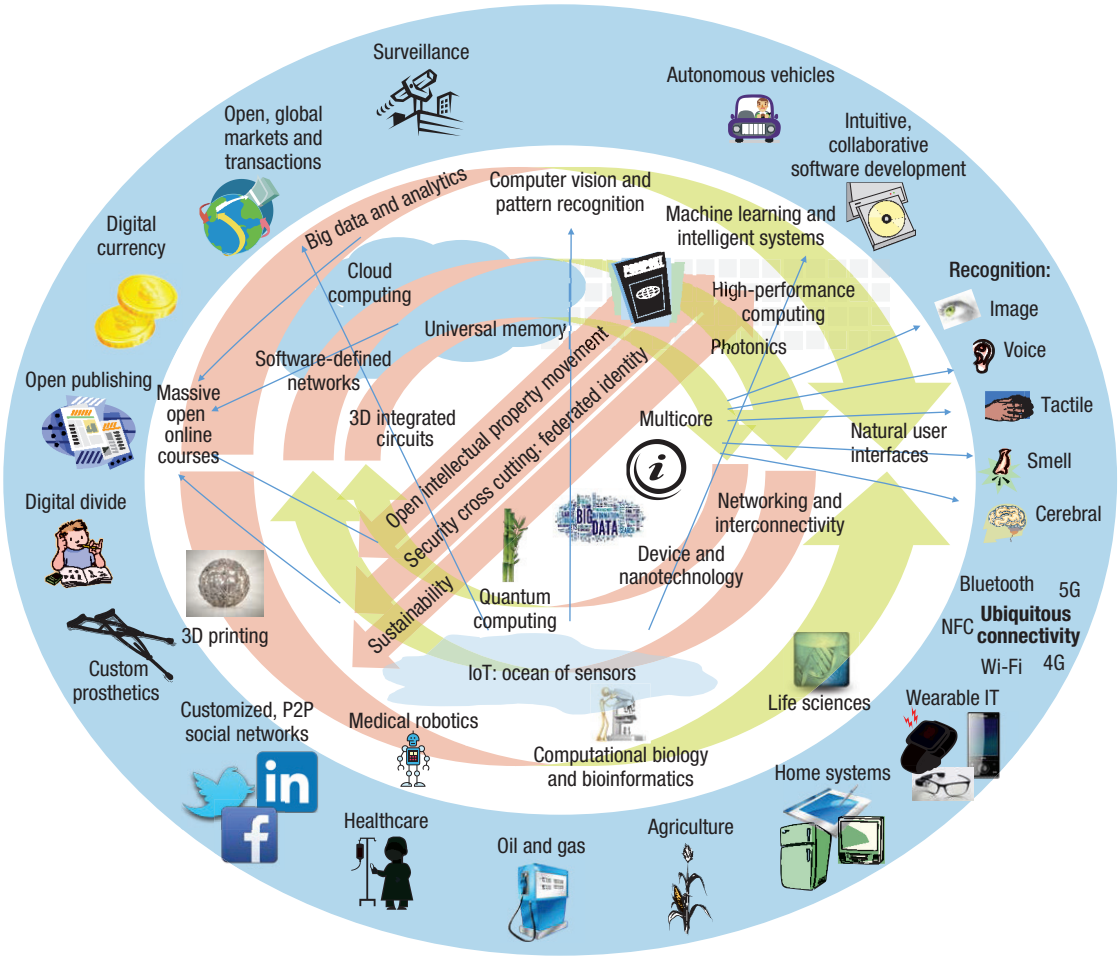

FIGURE 4. Visual interpretation of the 23 technologies and their seamless integration. The technologies, woven into a mesh of dependencies and impacts, influence many existing and future technology markets and verticals.

data with maps points to what future mashups might look like.

Loss of privacy

Pervasive and massive identity recognition could have myriad benefits: cashless and contactless financial transactions, the ability to cross borders without stopping for inspection, and walking into a coffee shop in a foreign country and having the barista offer up your favorite coffee because your preferences appeared on her counter screen as you approached the shop.

But the combination of more exact voice and facial recognition, massive identity databases, and powerful tracking that allow such convenience will also create new dangers, such as significant loss of privacy compared to today. New innovations will bring many benefits, but preventing misuse will both require new technology and involve collective social action.

WHERE WE THINK THE TECHNOLOGY WILL GO

Seamless intelligence and its integration will take a number of concrete forms in the future.

Healthcare

Imagine walking into a hospital in any city or country and not having to explain what medications you're currently taking or what immunizations your child most recently received. Your entire medical history would be available to the attending professional, accessible from a centrally managed health vault. This isn't possible today due to the lack of standardized electronic medical records and their supporting infrastructure (connectivity, identity control, global access, real-time analytics, and so on).

However, 3D printing already lets your dentist create a crown, bridge, or other dental appliance while you wait. In the future, physicians will also be able to use less invasive procedures, such as having a patient swallow a small camera to image the entire digestive track. Medication and medical devices could even be customized in real time.

Education

Seamless and pervasive intelligence is already proving disruptive in education, with traditional campus-based education models changing as new teaching methods evolve, augmented by automated and interactive learning outside the classroom and distance participation. By 2022, we expect that current experiments with MOOCs will lead to more refined models in which MOOCs are complementary to ongoing instruction models. We also project that courses will involve less instruction and lecturing and more dialogue with expert professors, resulting from the ability to use technology for interaction outside the classroom. Students will enjoy learning more, as it will require less time even as they can comprehend the subject material more deeply.

The future holds even more for the integration of work and education via augmented reality. For example, as someone is working, she will receive customized information that allows for progressive training. This scenario will revolutionize several sectors, including customer care training and learning new services and products.

Autonomous vehicles

Progress in robotics will likely lead the way to fully automated, autonomous vehicles. This vision is at least 60 years old, but advances in sensing technologies and the computational power to process them have only recently become available. Combined with seamless networking, this vision can be taken further.

Imagine, for example, a driverless taxi, just large enough to accommodate you and your baggage, dispatched to your hotel to take you to the airport, automatically navigating the best route along the way. It already knows your departure terminal from a prior seamless information exchange. Autonomous vehicles will transform the topology of urban areas, dynamically creating one-way streets and preferential lanes—and the traffic layout will change continuously.

Big data

Big data is at the core of seamless intelligence. Unlike past systems, major breakthroughs over the last few decades have come from correlating and leveraging vast amounts of social information. Efficient and massive computing power will continue to be a key enabler of the technology revolution.

Continuity in computing—from basic sensory processing, simple event and location tracking, and calendaring and collaboration support to personal applications—will be augmented by powerful computing in the cloud and massively distributed systems. Big data analysis will take place in the background, providing continuous intelligence to executives who run major organizations, enabling both the tracking and coordination of major business activities and strategic choices based on real-life data intelligence.

Cloud computing

Developments in cloud computing will transform computing from a physical experience into a virtual one available to any user via a simple device operating on ubiquitous networks with seamless connectivity. Large computations running on massive cloud infrastructures will yield results available as affordable services almost anyone can access and utilize.

However, history has taught us that increased processing power becomes available at the "edges of the network"—that is, through devices in the hands of users. In this regard, the cloud can be seen as a processing fabric, part of the ambient environment, and a commodity. Cloud-based implementations emerge as technicians and business leaders determine; to the end user, the underlying information systems architecture is irrelevant.

BY 2022, INTELLIGENCE WILL BE SEAMLESS AND UBIQUITOUS FOR THOSE WHO CAN AFFORD STATE-OF-THE-ART INFORMATION TECHNOLOGY.

Power consumption

Multicore and many-core technologies, coupled with new memory technologies like nonvolatile RAM, will provide the horsepower needed for automation and robotics—including medical applications—and their use will lead to greater power efficiency for cloud servers, high-performance computing systems, and wearable devices,

smartphones, and other elements of the IoT. Power consumption will be reduced not only by hardware improvements but also by software progress in compilers, runtimes, and operating systems. Significant savings in power consumption by 2022 will be complemented by numerous solar-powered wearable devices, smartphones, cloud servers, and nonstop servers—all of which may help save lives when natural disasters interrupt power delivery systems.

Security

Seamless and ubiquitous intelligence aids in enforcing strong security measures, thus achieving unprecedented safety levels. Smart sensors, surveillance cameras, and eavesdropping devices integrated with identity-recognition systems will allow law enforcement to track and capture or quarantine potentially harmful individuals while also monitoring officer conduct. Conversely, access to such intrusive technology can violate individuals' rights and invade the privacy of innocent people. Society will be obliged to limit the use of seamless intelligence within acceptable norms.

Social and political ramifications

Despite its promise, future seamless intelligence carries potential for concern. For instance, the technology gap between those who can afford certain enabling technologies and those who can't could increase. The seamlessness of a prosperous region would be missed when a traveler finds it impossible to use a smart card at a store or train station in an area that doesn't have that technology. Conversely, a traveler from a technologically poor area might find it difficult to obtain the services she needs when visiting a place where enhanced technology is common. The rapid evolution of increased automation and the spread of pervasive intelligence in everyday activities will accentuate the differences between wealthy and poor nations.

WE BELIEVE THE COMPUTER SOCIETY CAN BE AT THE LEADING EDGE OF SUPPORTING SEAMLESS INTELLIGENCE FOR ITS MEMBERS.

Nonetheless, many people, regardless of wealth, will continue to enjoy the results of advances in computing, partly fueled by the proliferation of open source software and hardware—particularly in inexpensive yet smart mobile devices. The trend is toward extending social networking rather than directly enhancing productivity tools. Furthermore, ubiquitous computational and educational services will grow ever more accessible to any population that meets the basic connectivity requirements. In the absence of entrenched legacy systems, new technologies will be able to achieve accelerated adoption, as was recently the case with cell phones and Twitter in developing countries.

But while seamless intelligence can be used for advancing healthcare, education, science, trade, financial services, social and political activism, security, and safety, it can also be used for militarization, to invade privacy, and to push the Big Brother phenomenon worldwide, even in countries that consider themselves and take pride in being "free."

POTENTIAL DISRUPTIONS

The growth in the mobile smart device sector over the past decade is likely to continue disruptions in traditional computing models for desktops and laptops. Mobile applications will further expand the Internet platform by enabling highly connected, smarter, and situation-aware applications everywhere.

At the other end of the computing scale, cloud computing based primarily on commodity server hardware is disrupting the traditional server sector, replacing it with computational power and virtually unlimited storage as a service over the network.

Another disruptive trend resulting from the spread of social networking could prompt certain countries and regions to create their own regional Internet, imposing restrictions on access to global sites and universal services. This trend might have a negative disruptive impact on the global Internet and individuals' freedom to obtain information and services regardless of geographic location and political boundaries. Regulation will also become an issue, with different regulatory agencies taking varying positions regarding premium connectivity.

Intellectual property wars among major players in the industry can

TABLE 1. Who will benefit from the IEEE Computer Society in 2020.

Who	How
Multidisciplinary professionals	Deliver highest-quality content in small units
Global citizens	Digest, synthesize, summarize, and repackage content
Knowledge seekers	Offer skills development and training
Volunteers who can devote small bits of time intermittently	Focus on "high touch" with small face-to-face meetings on the latest topics

present barriers to both the speed of progress and the use of technology. Consumers will ultimately be the victims of such wars.

THE IEEE COMPUTER SOCIETY IN 2022

So far, we have focused on the "what" and the "why" of future technologies, leaving two unanswered questions:

- Who will take up the work leading to our predicted future? This will require a focus on the development of the industry and its professionals. The CS will play an important role in fostering a highly skilled workforce.
- How can information technology fulfill its mission to benefit humanity? This will require a focus on technology's impact on society. The CS should also plan to raise awareness of the beneficial implementations of technology.

We believe the CS can be at the leading edge of supporting seamless intelligence for its members. IEEE CS members will be truly global and truly connected. Anyone who has an interest—regardless of location—should be able to instantly become an IEEE CS member and participate in special technical communities,[5,6] gain access to all CS products and services, and be connected with other members virtually or at face-to-face meetings.

Early use of technology by next-generation professionals will drive the average age of our members down 10 years or more. The invent-to-publish cycle will be much shorter, with almost instant access to materials, collaboration opportunities, and physical or virtual meetings. Crowdsourced peer review will be the norm, but new standards will demand high quality: communities will tend to code that evolves rapidly to respond to changing needs, and community members will enforce professional codes of practice and collaborate to develop "building codes" for secure infrastructure, as the CS is pursuing through its cybersecurity initiative (http://cybersecurity.ieee.org).

The relative value of these new products will be immediately apparent, as users will rate their benefits. While technology will always have its "cool factor," traditional engineering principles and rigor won't be compromised. The difference will lie in how knowledge is transferred. You will learn by doing and learn from other doers.

This new culture will give rise to more interactive events like hackathons, gaming conventions, and meetups. Traditional academic meetings will be joined by practitioner conferences, with the two complementing one another.

Recent developments in Internet security and privacy have eroded the universal view that technology advancement is always good. Seamless intelligence may not sound so positive to everyone. The CS must be mindful of preserving security and privacy as well as the overall use of technology. We must ensure that societal changes are at pace with technology, but not slower.

The CS has long been at the forefront of new technologies. For example, the CS used scenario planning in 2004 when it was developing Strategic Plan 5.1 (SP5) to imagine what the year 2020 might look like. Much of the 2004 scenario includes elements that are still current. Table 1 summarizes the SP5 predictions about whom the CS would serve in 2020 and in what ways.

If these 2020 future states are still relevant, how is the CS doing? The most recent SWOT (strengths, weaknesses, opportunities, threats) analysis conducted by the CS Board of Governors shows that we have developed some strength in these areas, but most of these challenges remain.

The second part of the *CS 2022 Report*, CS Strategic Plan 8, will address how the CS must be organized in the year 2022, in light of the technologies outlined in this article.

By 2022, computing devices will vary from nano- to megascale, and wireless and wired networks will enable access to integrated services. Virtual connectivity will allow for the integration of relevant computing resources to provide users with seamless services. The resulting ecosystem will offer continuous, uninterrupted services that enhance automation, productivity, collaboration, and access to intelligence and knowledge through emerging human–computer interaction.

However, the benefit of technology is what we make of it. How these technological advancements help humanity will depend on the pace of the policies and regulations that accompany the technologies' evolution. Technology is an enabler: it's up to us to leverage it in the best possible way to advance humankind.

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