NISTIR 8348

National Institute of Standards and Technology Environmental Scan 2020

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National Institute of Standards and Technology
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Preface

In preparation for the launch of a strategic planning effort in 2018, the NIST Program Coordination Office (PCO) developed the 2018 NIST Environmental Scan to provide context for NIST senior leadership in developing that plan. While the Strategic Plan was completed and implementation is now underway, it is valuable to regularly assess the key issues facing NIST; this manuscript serves that role by re-examining the findings from the 2018 environmental scan. As with the 2018 scan, the analyses herein are not intended to be a comprehensive list of all opportunities for, and threats to, NIST. Instead, they highlight significant trends and developments that may impact NIST in the next ten years. Any viewpoints and recommendations are made strictly based on observations and are not an official NIST position. In developing this scan, the PCO staff used a variety of external sources, which are cited in the References section.

Abstract

The 2020 National Institute of Standards and Technology Environmental Scan provides an analysis of key external factors that could impact NIST and the fulfillment of its mission in coming years. The analyses were conducted through four separate lenses: Societal, Investment & Geopolitical, Political & Policy, and Technology & Science. Most of the issues discussed in the initial environmental scan conducted in 2018 are still relevant, but a number of key issues have emerged in society that will impact NIST since the writing of that report, most notably the COVID-19 pandemic and the national discourse around race. Societal, political, financial, and workforce issues will challenge NIST to maintain and advance its leadership in metrology, standards, and technology. However, a broad range of emerging technology issues present opportunities for NIST to have significant impact in advancing the nation’s innovation and industrial competitiveness.

Key words

Environmental Scan; NIST Policy; Strategic Planning 2020.

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1. Introduction

Since its inception as the National Bureau of Standards (1901), the National Institute of Standards and Technology (NIST) has played a defining role in standardization and innovation in the United States (U.S.). Situated within the U.S. Department of Commerce (DOC), NIST's mission is "to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life." This mission is achieved through NIST's core competencies of measurement science, rigorous traceability, and the development and use of standards, as well as core organization values of perseverance, integrity, inclusivity, and excellence. As NIST maintains consistency with its core competencies and organizational values, it is imperative that NIST be organizationally and programmatically nimble so that its programs can respond to changing technologies and societal needs. In 2020, as NIST plans for the near- and mid-term future, decisions must be made about where efforts should be placed to most effectively execute the NIST mission.

This updated and expanded document builds on the 2018 National Institute of Standards and Technology Environmental Scan, published as NIST Internal Report 8244 [1], updating topics and presenting new ones in areas where the global landscape has changed. Environmental scans provide a mechanism for gathering prospective information during strategic planning exercises. They provide insights into external factors that may influence how an institution plans and operates. In an attempt to provide a holistic view of the current environment, this exercise was conducted through four separate lenses: *societal*, *political*, *geopolitical*, and *technological*.

The following sections address the views through each of these lenses and provide an informative breakdown of ongoing trends in the current global environment. These trends may not directly influence NIST's strategic direction (see current 2020-2025 Strategic Plan [2]) but will likely impact mission-oriented decisions of the future, including decisions on workforce, processes, and partners.

2. Societal Landscape

The societal landscape scan focuses on two major trends: societal changes and the information divide/distrust of science. The subtopics addressed include: the aging population and generational divides of the U.S.; immigration trends; social impact; diversity and inclusion in the workplace; income and wealth gap; the information divide; techlash; and distrust of science, technology, and the nation's institutions. The Black Lives Matter (BLM) movement and COVID-19 pandemic are two notable additions to this section.

2.1. Societal Changes

Overall, the U.S. population is projected to grow at a slower pace, age considerably, and become more racially and ethnically diverse. More generations are working side-by-side than ever before, with the youngest generation valuing socially responsible companies and institutions. Equity and supportive, inclusive workplace cultures are major issues being addressed across multiple sectors. As the workforce becomes more diverse, it demands a change in the status quo.

2.1.1. Aging Population and Generational Divides

According to the U.S. Census Bureau, starting in the year 2030, one in every five U.S. residents will be older than age 65 (including the baby boomer generation). Older adults are expected to outnumber children for the first time in U.S. history by 2034. Dubbing this phenomenon "a graying nation," the Census Bureau also notes that similar trends are observed in other nations including Japan, Canada, and many European countries that are already grappling with these challenges [3]. This projection presents a major challenge for federal programs such as Social Security and Medicare, but also suggests that working adults may have increased caregiving responsibilities as life expectancies continue to increase due to modern medicine and healthcare. In turn, this may also be reflected by a higher desire by employees to work remotely.

For the first time in U.S. history, in 2016 five generations constituted the workforce, with millennials representing the largest generation (Fig. 1).

Generations

Generation Z/post-millennial
Born 1997 or later

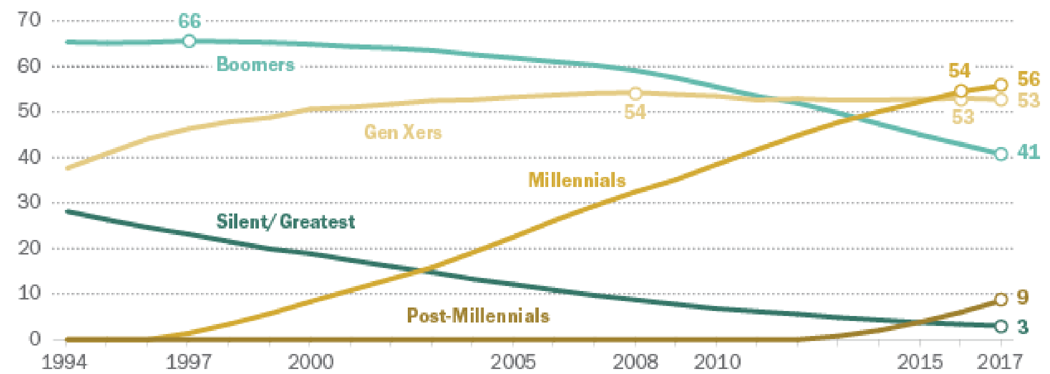
Millennial
Born 1981-1996

Generation X
Born 1965-1980

Baby Boom
Born 1946-1964

Silent and Greatest
Born 1945 or earlier

Source: Pew Research Center [4]



Note: Labor force includes those ages 16 and older who are working or looking for work. Annual averages shown.
Source: Pew Research Center analysis of monthly 1994-2017 Current Population Survey (IPUMS).

PEW RESEARCH CENTER

Fig. 1. U.S. Labor Force, in millions, from 1994 to 2017 by generation, showing millennials leading in 2017. [4]

The Millennial generation is different from others in many ways. Millennials have a higher educational level than previous generations (e.g., having a bachelor's degree or higher): 39 % for millennials; 29 % for Gen X; 25 % for Boomers; and 15 % for Silent. They are less likely to be married than previous generations at the same age, and millennial women are more strongly represented in the workforce. In 2018, 75 % of millennial women were employed compared to 66 % of women in the baby boomer generation and 40 % of the women in the silent generation. In line with overall population trends, diversity is also rapidly increasing with younger generations. Generation Z is projected to be the most diverse of all, with nearly 50 % of people being from traditionally underrepresented racial or ethnic groups [5]. The differences in life experiences and context of these populations can lead to workplace conflict. For example, tension could arise between generations related to work locations and hours (e.g., telecommuting, flexible work schedules, holidays), gathering and sharing salary and promotion information, and communication preferences (e.g., face-to-face meetings, phone calls, voice messages, emails, texting, or instant messaging).

2.1.2. Immigration Trends

Immigration trends influence nearly every policy area of concern, from jobs and the economy, to education, health care, and federal, state, and local government budgets. An extensive National Academies study examined the economic and fiscal consequences of migration by exploring the current trends in immigration, outlining the socioeconomic outcomes of immigrants in the nation, and describing the broad economic impacts that migration to the U.S. has on labor, wages, production, consumption, and economic growth [6]. The report called out the importance of immigration for the nation's economic growth and stated that "the infusion by high-skilled immigration of human capital has boosted the nation's capacity for innovation, entrepreneurship, and technological change."

The number of immigrants living in the U.S. continues to increase. According to the U.S. Census Bureau projections, the international-born population in the U.S. will reach a historic high of

14.9 % in 2028, higher than any time since 1850. They project that by 2030, net international migration will overtake U.S.-born birthrate as the primary driver of population growth in the U.S. [3]. This increase is also likely to affect the workforce and overall demographics of the population. However, the predictions do not factor in any new or significant immigration policy changes.

A recent study explored the influence of science, technology, engineering, and math (STEM) studies by immigrant children and found that the age at immigration and first language can influence a child's high school coursework and college majors [7]. The authors identified immigrant children arriving in the U.S. after age 10 and traveling from countries with a language dissimilar to English as the group most likely to major in STEM fields in college. Of these students, 36 % major in STEM fields compared to about 20 % of U.S.-born students.

Public perception of immigration may also be shifting. According to a recent Gallup poll, U.S. adults are more likely to say that immigrants improve life in the U.S. than when surveyed in 2007. According to the poll, most Americans now say immigration is positive for the country (77 %), steadily increasing up from 60 % in 2007 and at the highest level since the poll started in 2001; also, 84 % believe legal immigration is good for the country [8].

2.1.3. Social Impact

Social impact has become quite important for younger workers. For example, a 2016 Cone Communications study revealed that 75 % of millennials would take a pay cut to work for a socially responsible company. Eighty-eight percent say their job is more fulfilling if there are opportunities to positively impact a social or environmental issue [9]. They also found that the majority of millennials (75 %) consider a company's social and environmental commitments before deciding where to work and the majority (64 %) would not take a job if a potential employer doesn't have strong corporate responsibility practices. The 2018 LinkedIn workplace survey found similar results, showing 71 % of professionals would be willing to take a pay cut to work for a company whose values they share [10].

2.1.4. Diversity and Inclusion in the Workplace

While great strides have been made over the last few decades, with an increasing number of women in leadership positions, sustained progress towards closing the "gender gap" will not occur unless persistent sexual harassment is addressed. A National Academies 2018 study found that 20 % to 50 % of women in science, engineering, and medical academic settings experienced some form of harassment, including gender harassment (most common being verbal or nonverbal sexist hostility and crude behavior), unwanted sexual attention (unwanted verbal or physical advances), or sexual coercion (favorable treatment conditional on sexual activity) [11]. When women experience sexual harassment at work, they can suffer in multiple ways: by becoming less involved in the organization, leaving a job, or even leaving the field. These implications feed into the prominence of women in lower level positions and far fewer able to navigate the promotion ladder. There is a perception that bad behavior is excused or ignored by managers. This perception results in women voluntarily leaving jobs due to workplace culture and harassment. The "broken rung" that occurs when women are not elevated to junior managerial positions prevents women from moving upward into managerial posts and eventually making their way to senior management roles.

Experiences of traditionally underrepresented groups in STEM is also a critical issue. Following a series of traumatic events in 2020, including the deaths of George Floyd and Breonna Taylor at the hands of police, the Black Lives Matter movement gained momentum and prevalence in discourse across the nation and the world. Scientists organized a 'Strike for Black Lives' on June 10, 2020 where they asked for non-Black participants to take actions centered around making change in scientific institutions. Many leading scientific organizations shut down their activities to spend time addressing anti-racism and signaling the need for their communities to do better at inclusion of black and other marginalized colleagues [12]. This inward reflection continued throughout the summer of 2020 with many companies and organizations announcing plans of action to combat internal systemic racism and bias [13].

The issue of workplace diversity is an intersectional issue that includes factors of race and gender. For first-level management positions in the corporate world, women are promoted at 72 % the rate of men, with Latina and Black women promoted at 68 % and 58 %, respectively. This further constrains progress, as women get stuck in entry-level positions, and there are fewer women to promote at higher levels [14]. Looking at pipeline issues, a landmark report published by the American Institute of Physics shows long-term systemic issues that have resulted in the underrepresentation of African Americans in the field of physics [15].

Worldwide, women account for over half of STEM bachelor and master degrees, but only about 30 % of researchers, thus indicating a retention problem in the workforce [15]. An issue that may impact retention is harassment of women. To combat pervasive harassment in the STEM workplace, care must be taken to create diverse, inclusive, and respectful environments, where individuals are supported, and gender harassment is neutralized. This environment includes effective mentoring, which has been shown to help retain women and traditionally marginalized groups in STEMM (science, technology, engineering, mathematics, and medicine) by giving them an example of someone on their career path with a similar background, and providing professional development and leadership opportunities.

Having a diverse workforce has repeatedly been shown to improve productivity and innovation, and having more women in the workplace can improve employee engagement and retention [16]. About $8 billion is spent each year on diversity and inclusion training in the U.S., but little progress has come out of these initiatives. Therefore, more research on effective practices is needed [17]. Two bills introduced in the 116th Congress (Combatting Sexual Harassment in Science Act and STEM Opportunities Act) would provide funding for research on harassment and discrimination in STEM and identify barriers to entry in STEM fields.

There are several evidence-based best practices used to recruit and retain a more diverse and supported workforce. These practices include actively expanding recruitment networks, posting broader and more inclusive job descriptions, and evaluating how unconscious bias impacts the hiring process. Making the promotion process more transparent, including junior employees in the process, and expanding what STEM contributions are valued can help improve retention. Along with mentoring programs, sponsorship of women and marginalized groups by senior leadership is also important because sponsors have the clout to publicly advocate for promotions and career advancement of others [18]. Those people in positions of leadership can also improve recruitment and retention of a more diverse workforce by taking training to become aware of their internal bias and providing concrete actions to mitigate this bias, especially in hiring and promotion, as well as training to lead diverse teams. There is still a long way to go, but by making changes such as implementing meaningful and sustained trainings, outlining clear expectations and consequences, and continuing to solicit feedback and monitoring progress, the culture of the STEM workplace will become more inclusive.

2.1.5. Income and Wealth Gap

The gap between those with the most and least material wealth in the U.S. has been increasing in recent years. This gap exists in both annual income and overall wealth. From 1979 through 2018, the real hourly wages of production and nonsupervisory workers grew by 11.6 % despite productivity growing by 69.6 %. This difference was largely captured by higher corporate profits and increased wage growth of the highest earners. Over this same time period, the top 1 % of earners saw an increase in real annual wages of 158 % and the top 0.1 % of earners saw earnings grow 341 % [19]. The rising gap gives the U.S. the highest level of income inequality of any G7 country. Amongst countries tracked by the Organization of Economic Co-operation and Development (OECD), the U.S. ranked 31 out of 35 countries in terms of income equality [20]. The gap in wealth is also increasing. From 1983 to 2016, the share of aggregate wealth held by upper income families increased from 60 % to 79 %. This rise was largely at the expense of middle income families that saw their share of aggregate wealth drop from 32 % to 17 %. The share attributed to lower income families also decreased, from 7 % in 1983 to 4 % in 2016 [21].

The income and wealth gaps have different impacts depending upon demographics. In 2018, the real median income for households led by an Asian individual was over $87,000 per year, whereas households led by Black individuals reported a median income slightly more than $41,000 [22]. It appears that income inequality is increasing within racial groups over time as indicated by the ratio of real median household income to real mean household income. That ratio has decreased across racial groups from 1980 to 2018. It should also be noted that the COVID-19 pandemic is expected to exacerbate these disparities. Employment in low-wage occupations, which is heavily made up of Black and Hispanic workers, fell 19.8 % from February 2020 to May 2020. Employment in high-wage occupations in which white and Asian workers represent the majority demographics fell by only 3.6 % in the same time period [22].

2.2. Information Divide/Distrust of Science

Today's society can be characterized by increased polarization and distrust of science by a segment of the population, fueled by a variety of factors.

2.2.1. Information Divide

Differences in perspectives are heightened by the digital age of information exchange that allows for facts and opposing 'counter facts' to look identical, making some individuals vulnerable to accepting and acting on misinformation. One contributing factor is income inequality as discussed in the previous section. Another contributing factor, according to a Washington Post-Kaiser Family Foundation survey of nearly 1700 Americans, is a growing divide between communities based on misgivings about demographic changes and perceived biases in federal assistance [23]. "Alongside a strong rural social identity, the survey shows that disagreements between rural and urban America ultimately center on fairness: Who wins and who loses in the new American economy, who deserves the most help in society, and whether the Federal Government shows preferential treatment to certain types of people" [24].

A 2016 study of 920 news outlets and 376 million Facebook users found that the Facebook news sphere is clustered and dominated by a community structure, and that users tend to focus on a single group of like-minded news outlets [25]. The intermingling of information dissemination and social platforms in the digital age has resulted in disparate communities of people who not only have differing viewpoints, but do not agree on a single set of information or facts on which those viewpoints are based. Social scientists have investigated the ways that people absorb information and form beliefs. Social contagion, or the tendency to think and act like close acquaintances, the framing of messages to evoke existing beliefs, and a person's worldview are all key ways that information takes hold [26]. When these three factors vary for different people, alternative perceptions of fact emerge.

Conflating information and misinformation wreaks havoc on a society. The COVID-19 pandemic illustrates the challenges of misinformation propagated throughout social media. In his remarks at the Munich Security Conference on February 15, 2020, the Director-General of the World Health Organization (WHO) Tedros Adhanom Ghebreyesus said, "We're not just fighting an epidemic; we're fighting an infodemic. Fake news spreads faster and more easily than this virus, and is just as dangerous." [27]. To help curb the issue, the WHO created a series of "Myth Buster" infographics to help advise the public on alleged COVID-19 cures and other related information [28]. In the ensuing months, the WHO itself became a prime target of distrust. In May 2020, President Trump announced the U.S. would withdraw from the organization, claiming the WHO misled the public and fumbled the COVID-19 pandemic response (the President's letter to WHO prompted responses from scientists including a statement from the Lancet) [29].

The issue of mask-wearing served as a partisan flashpoint for many Americans, with much finger-pointing between political groups over the effectiveness of masks and whether mandating their use infringed on personal liberties [30]. Over time, the public health community learned about the efficacy of face coverings in preventing the spread of COVID-19 and eventually, the CDC evolved its guidance to unambiguously encourage people to wear face coverings [31].

Separating truth from fiction will only become more difficult with the use of voice- and video-morphing technology. "If trust in what politicians say is already low, it could soon be non-existent," writes reporter Rachel Botsman, adding that, "artificial intelligence and augmented reality, for example, will mean that we'll have to question everything we see, hear, or read forensically, to decide if it's the real deal or clever fakery" [32]. With the advent of more sophisticated and accessible machine learning algorithms, deepfake videos and audio recordings are becoming easier to create (and more difficult to identify) according to a recent IEEE article [33].

2.2.2. Techlash

Society is continuously connected to an influx of information while simultaneously generating and exposing new types of personal data. Smartphone owners interact with their phones an average of 85 times per day, including immediately upon waking up, just before going to sleep, and even in the middle of the night. This state of continuous connection is new: only 4 % of U.S. adults owned smartphones in 2007, while today, that number has skyrocketed to 81 % [34]. According to the National Highway Traffic Safety Administration, 3450 people were killed in 2016 in motor vehicle crashes involving distracted drivers [35]. A 2017 study concluded that of the 1787 U.S. 19- to 32-year-olds surveyed, those who spent the most time on social media (more than 2 hours per day) had twice the rate of perceived social isolation than those who spent 30 minutes or less per day on social media sites [36].

Data governance, consumer privacy, and disinformation remain constant challenges, as Cambridge Analytica's use of data from at least 50 million Facebook users (illegally in some instances) started raising important questions [37]. Large social media platforms are now under further scrutiny as the public becomes aware of the use of personal data and the presence of fake news, hate speech, and political ad sponsorship. In the past, both Facebook and Twitter said they should not be "arbiters of the truth." However, both have shown an ability to address false information in certain circumstances. For instance, in an effort to avoid disinformation spreading as it did before the 2016 U.S. presidential election, Facebook announced it would not run new political ads in the week prior to the 2020 election and would remove posts that encouraged voter suppression [38]. During the COVID-19 pandemic, Facebook took down COVID-19 conspiracy theory posts, and Twitter deleted several posts spreading false information about the virus [39]. Although these instances may be seen as progress, the way social media platforms address disinformation is not always consistent.

Multinational companies are also under increased scrutiny. President Trump signed an Executive Order to restrict or ban TikTok (ByteDance Ltd.) and WeChat (Tencent Holdings Ltd.) over security concerns that the Chinese-owned apps would use citizen data to collect and release American user information to the Chinese government [40].

The European Union (EU)'s General Data Protection Regulation (GDPR) went into effect on May 25, 2018 [41]. Intended to protect the processing and sharing of personal data, the GDPR applies to any company processing personal data of a person residing in the EU. As such, companies are required to put technical and organizational measures in place. For example, companies must disclose any personal data collection (and the basis for the collection) and must report any data breaches within 72 hours. The regulation also outlines penalties for companies found to violate the GDPR. Due to the international extent of online business transactions, many companies in the U.S. have adjusted their policies and websites to accommodate the GDPR requirements, frequently implemented by a pop-up window that visitors must click on, outlining a website's policy on collecting cookies and other details about their privacy policy. In the U.S., there have been some state-level acts put in place, like the California Consumer Privacy Act of 2018 [42]. At the federal level, version 1.0 of the NIST Privacy Framework was issued in January 2020. Differing from the EU's legally-binding approach, the privacy framework is a voluntary tool for improving privacy through enterprise risk management, designed to be compatible with existing domestic and international legal and regulatory regimes and usable by any type of organization to enable widespread adoption [43].

As the use of personal information becomes public knowledge, citizens are intuitively challenging the 'move fast and break things' Silicon Valley mindset and business model while pointing fingers at technology companies for failing to earn the trust of society. This topic was covered at the 2018 World Economic Forum Annual Meeting. Participants proposed a theory that at the heart of techlash is a movement towards a future that will benefit the planet and the human experience; however, to reach this future, institutions must listen to and respond to technology backlash in a way that results in the development of technologies that will benefit society and that society can trust [44]. This trend is likely a driver of the above-mentioned desire of younger workers for "social impact." Tied into this backlash and focus on social justice is the #StopHateForProfit campaign led by civil rights activists, where companies pulled advertisements from Facebook in July 2020 in response to their lack of action to curb hate speech and violence on the social media site [45].

In the summer of 2020, several tech companies announced plans to temporarily halt sales of facial recognition technologies. These decisions appear to be motivated by potential injustices of the application of the technology owing to the lack of policy guidelines, and known performance deficiencies for some demographics [46]. On June 8, 2020, CEO Arvind Krishna announced that IBM would no longer offer facial recognition technology until responsible technology policies were in place that do not promote discrimination or racial injustice, stating "IBM firmly opposes and will not condone uses of any technology, including facial recognition technology offered by other vendors, for mass surveillance, racial profiling, violations of basic human rights and freedoms, or any purpose which is not consistent with our values and Principles of Trust and Transparency" [47]. That same week, Microsoft President Brad Smith announced his company's intent not to sell technology to any law enforcement agencies until a federal law is in place about the technology's use [48]. Some state and local governments are considering banning or have already banned the use of facial recognition technologies in their communities [49].

2.2.3. Distrust

Based on the prior subtopics, one can surmise that widespread distrust in the U.S. is on the rise. For the past twenty years, the Edelman global communications firm has issued an assessment of trust around the globe. In 2020, the Edelman Trust Barometer trust index (the average percent of trust in four institutions: non-governmental organizations, business, government, and media) set a new record low for trust inequality between the informed public and the mass population. The latter group did not trust any of the four institutions based on attributes of competence and ethical behavior. Over 60 % of respondents in the Edelman Trust Barometer worry that technology is out of control, agreeing with the following three statements: "I worry technology will make it impossible to know if what people are seeing or hearing is real;" "The pace of change in technology is too fast;" and "Government does not understand emerging technologies enough to regulate them" [50]. Ironically, when news media attempts to provide balanced information by having "experts" present on both sides of an issue, it can lead to an incorrect perception of the scientific process and the accuracy of scientific data, thereby leading to a distrust of data and conclusions.

2.3. Implications for NIST

2.3.1. Workforce

As the population ages and stratifies, the differences between the five generations will be exaggerated in the workplace. Generational-based conflict in teams stems from differing expectations around when and where to work (e.g., telework or flexible schedules), modes of communication (e.g., face-to-face meetings, voicemails, emails, instant messages), scheduling (e.g., use of calendar software) and obtaining new skills (e.g., taking a formal course or learning on the fly) [51]. Workplace bias against others for reasons such as working different hours, using an 'impersonal' style of communication, failing to keep their calendar up to date, or using an online video to learn how to complete a work task can inhibit the collaborative team environment that NIST thrives upon.

However, some experts note that generational differences may be less important than they appear. For example, preferences can shift over time as individuals in any generation adjust to technology [52]. The experts also note that for critical conversations on topics like performance reviews and career planning, all generations prefer face-to-face interactions. Forthright and open discussions about workplace expectations, without implicating ageism, can bring attention to preferences caused by generational gaps. Differences in generational workstyles may affect how well new technology and software tools (e.g., new online systems used to record time and attendance, book travel, and track property) are accepted by NIST staff. In recent years, the Office of Human Resources Management added new training opportunities to equip staff with skills for success in inter-generational workplaces.

It should be noted that women have been disproportionately impacted by extra caregiving duties during the COVID-19 pandemic [53]. As the population ages, more NIST staff may find themselves as caregivers. The continued support of flexible work schedules (to include remote work), along with caregiver support groups, is needed. Although the population is aging, NIST cannot assume that the retirement rates will trend with the rates of individuals entering typical retirement age. The general trend projected by the U.S. Census Bureau is that older people are currently working and will continue to work for an increasing number of years and earn more annually [54]. This may have significant implications for staff advancement, gender equality, and the ability to recruit and retain skilled talent at NIST.

It is likely that the desire for remote work will increase substantially due to several trends, including the need for NIST employees to fulfill roles as caregivers, desire for workplace flexibility, and shifts in opinion due to working remotely during the COVID-19 pandemic. In addition to a changing attitude towards routine telework, NIST may also reevaluate remote stations, allowing employees greater flexibility in where they choose to live. As the COVID-19 pandemic stretches on, NIST must consider what workplace implications to adopt permanently, considering the possibility of future pandemics. The ability of staff to work remotely is easier to accommodate long-term in some parts of NIST (e.g., administration and Innovation & Industry Services) than other parts that perform experiments onsite (e.g., laboratory research). The relative benefits of working remotely will also need to be balanced against some of the costs, including fewer opportunities for social interaction and serendipitous conversations. According to staff, these are important aspects of working at NIST that help reinforce the NIST culture.

With core values of perseverance, integrity, inclusivity, and excellence, NIST staff are dedicated to their work at NIST and feel that their work makes a difference in the world. As millennials enter the workforce, these attributes may attract them to NIST over other opportunities. Increased location and telework flexibility may also help NIST recruit and retain talent pools previously overlooked.

2.3.2. Immigration

The immigration of highly skilled and educated individuals to the U.S. has long been an asset for NIST. The significant associate population at NIST consists of a substantial fraction of international guest researchers. Considering the immigration projections described above, it is likely that NIST could see an increase in international guest researchers over the coming decade. If the past is any indication, NIST will benefit from continuing to attract top performers. NIST has traditionally had great strength in this area, but changes in federal policies regarding immigration could affect the availability of these individuals to work alongside NIST staff. More about these trends is described in other sections of this report.

2.3.3. Diversity and Inclusion in the Workplace

In recent years, NIST has taken several steps to address diversity and inclusion in the workplace. One of the most prominent actions was to establish the Steering Group for Equity in Career Advancement (SGECA), which has supported efforts to create additional training and staff engagement opportunities, including two equity cafes held in 2019 on the Gaithersburg and Boulder NIST campuses, and offering new courses as part of leadership and management training curricula. The group has served as an advisor to senior NIST management on issues such as reviewing laboratory criteria for pay band V promotions, and has conducted events for staff, such as the inclusivity summit for NIST managers and supervisors held in April 2019. The SGECA works closely with affinity groups at NIST such as Women in STEM (wiSTEM), Pride, the Association of NIST Asian-Pacific Americans (ANAPA), and the Association of NIST Hispanic Americans (ANHA) to coordinate efforts and address staff needs. These affinity groups play an important role in cultivating an inclusive workplace for NIST staff.

In 2019, NIST initiated several efforts to gather data to understand and develop plans to address issues of equity, diversity, and inclusion. NIST awarded an 18-month contract in September 2019 to the University of Oregon COACh program to analyze the NIST career advancement process for STEM disciplines, identify critical factors in promotion disparity, and make substantive recommendations for sustainable approaches and methods that NIST can put in place. In addition, two staff members were selected for a one-year rotational assignment in the office of the ADLP to study equity, diversity, and inclusion, conducting research projects on inclusivity of women at NIST, and an inclusivity network analysis to harness innovation at NIST. Results from these studies are anticipated in fall 2020 and spring 2021.

In 2020, NIST launched two programs to improve the workplace culture at NIST. First, the Office of Human Resources Management kicked off a new NIST-wide mentoring program to help federal employees build strategic relationships and enhance their careers, starting with 75 mentor-mentee matches. Second, NIST established an Organizational Ombuds Program to provide support and assistance to members of the NIST community in addressing work-related conflicts. Both programs are considered best practices in building inclusive workplace environments.

Despite these purposeful steps toward a culture of inclusion, NIST struggles to attract and retain a diverse workforce. Staff are frustrated with the lack of action being taken and many have a perception that first-line and mid-line managers choose to excuse the bad behavior of top science performers, rather than remove the individual (or otherwise hold them accountable). It seems that some staff do not appreciate how NIST's core value of excellence can be met while also achieving its core value of inclusivity. In recent years, the Civil Rights and Diversity Office has started discussions across campus on civility to promote a respectful workplace culture and bring these two values into alignment.

There is anecdotal evidence from early career staff that many aspects of the NIST workplace are out of step with today's cultural norms; the institute is "behind the times" in widely embracing diverse communities and putting flexibilities in place that are common within private-sector workplaces. The Strategic Plan Action to institute a Diversity Leader can help advance progress. In the meantime and due to the perseverance of staff, some diversity initiatives, like the implementation of gender-neutral restrooms, were successful. Other initiatives need work. Specifically, in the summer of 2020, racial injustice in the broader world catalyzed discussions across NIST regarding racial inequities and the steps that staff and leadership should take to address the issue. In this endeavor, outcomes and long-term results remain to be seen.

We note that measures to track progress in creating a more diverse and inclusive workplace are lacking. There is a need for NIST to take these issues seriously and ensure the organization benefits from all efforts.

2.3.4. Income and Wealth Gap

In carrying out its mission, NIST will need to be mindful of the beneficiaries of its work. With its focus on increasing industrial competitiveness, consideration should be paid to the ways in which NIST work will impact workers. Additionally, many of the advanced technologies that NIST is enabling will require workforce training to ensure that less skilled workers are not left behind when the economy moves to those new technologies. Workforce development may be a role that organizations and activities such as the Hollings Manufacturing Extension Partnership (MEP), Manufacturing USA, and the National Initiative for Cybersecurity Education (NICE) could assist the U.S. with to minimize the growing income and wealth gap.

2.3.5. Distrust and Skepticism

As a non-regulatory institution with deep technical expertise, NIST has the reputation of being a trusted organization within the scientific community. In the current climate of distrust and skepticism, especially the mistrust of science, there are fewer institutions that remain avowedly objective and unbiased. An organization that prides itself on its objectivity and lack of scientific bias, NIST has positioned itself as the federal "trust" agency. Stakeholders from across a range of sectors speak highly of valuable interactions with NIST [55]. There is an opportunity for NIST to step up and reassert its role as a "trust" agency with strong scientific underpinnings that lack political agendas.

The general climate of distrust and skepticism, compounded by the information divide, could have far-reaching, harmful effects on the reputation and "brand" of NIST. One way to combat distrust may be to reinforce the culture of trust within NIST leadership and as an organization. It is important for NIST leadership to be especially cognizant of the appearance of their actions, as any ineffectual communication or lack of transparency from senior leadership may stoke distrust amongst the NIST community and affect external perceptions. In addition, a powerful avenue to ensure NIST's continuing quest for excellence is through effective engagement with the broader U.S. community. One opportunity would be to incentivize more NIST technical staff to be trained as communicators and serve as "science ambassadors" who give science popularization presentations to the general public, public schools, student bodies, etc. This outreach would be especially powerful, given the statistics from the Edelman Trust Barometer and because it would have an important social impact factor for staffing potential of NIST millennials.

3. Investment and Geopolitical Landscape

The current geopolitical landscape is fiercely competitive along several critical dimensions, including research and development (R&D) investment and technological innovation.

3.1. Worldwide Trends

By examining worldwide trends, this section evaluates potential impacts to NIST's core identity as a National Metrology Institute (NMI), along with NIST's standing on the world stage as a result of changing U.S. and global dynamics in R&D investments.

3.1.1. R&D Investment

The U.S. has long been recognized as a global science and technology (S&T) leader, with a budget reflecting this leadership stance. In 2018, U.S. spending on R&D accounted for approximately 40 % of the total Organization for Economic Co-operation and Development (OECD) countries' R&D expenditures ($555.1 billion across the 37 member countries). However, the U.S. leadership position is not secure. China is rapidly growing, with $526.1 billion reported spending, and the combined EU countries spending $428.4 billion over the same period. In terms of growth, since 2000, U.S. R&D spending increased slowly and steadily by approximately 35 %. This growth is in stark contrast to China where R&D spending increased by 92 % [56]. In terms of worldwide R&D expenditures, China outspent the U.S. from 2000 to 2017, contributing 32 % to worldwide R&D expenditure growth, compared to 20 % from the U.S. (Fig. 2) [57].

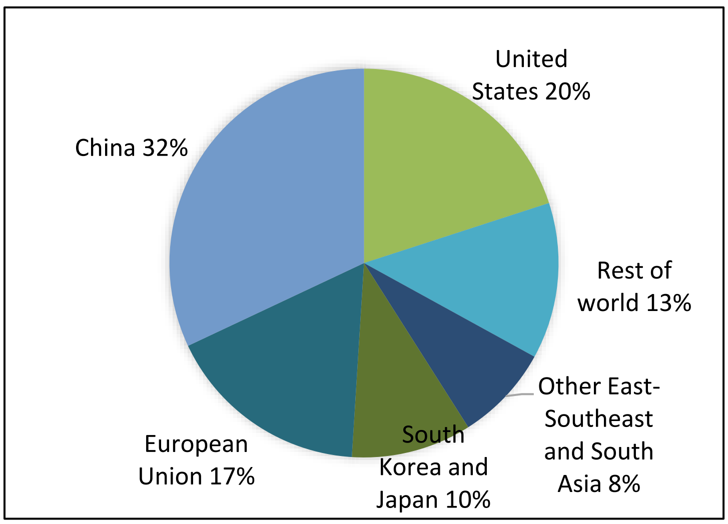


Fig. 2. Contributions to Worldwide R&D Expenditure Growth, 2000 to 2017. [56]

Furthermore, when considering the relative percent share of worldwide R&D expenditures, the U.S. actually witnessed a significant decrease between 2000 and 2017 (Fig. 3) [57]. This decline in percent share of worldwide R&D expenditures appears to be due to the large collective increase by East-Southeast and South Asia, including China.

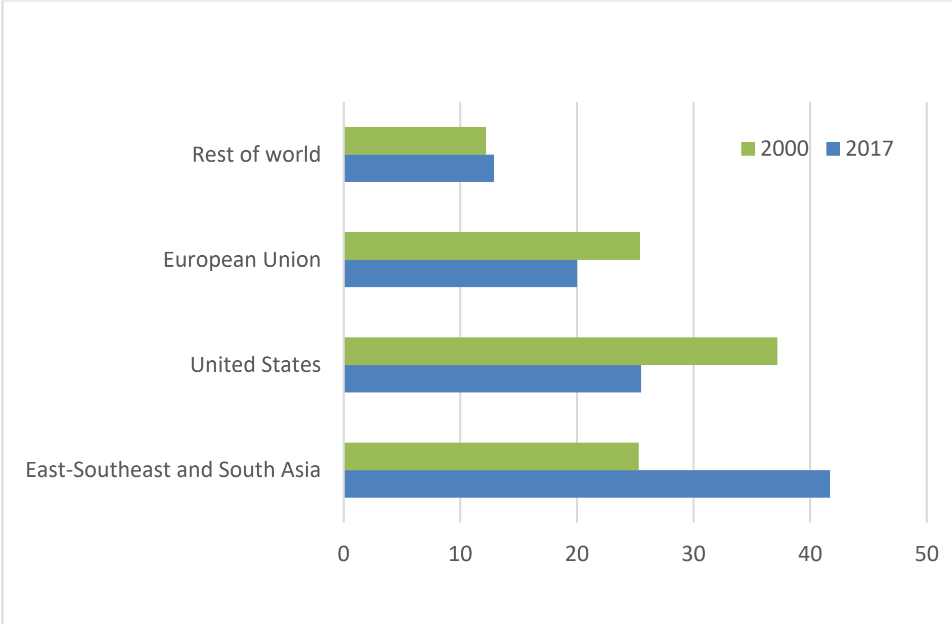


Fig. 3. Shares of Worldwide R&D Expenditures in 2000 and 2017. [57]

In 2017, China's President Xi Jingping announced plans to make China the world's biggest superpower by 2050, and the country has outspent OECD countries on R&D through 2020. It is important to note that the COVID-19 pandemic makes it difficult, if not impossible, to predict the effect that current events will have on R&D spending in the coming years.

In addition to understanding U.S. R&D spending in the broader international context, it is also informative to examine funding trends within the U.S. at a more detailed level. The U.S. business sector performed the vast majority (73 %) of U.S. R&D in 2017, followed by higher education (13 %), and the Federal Government (10 %) [57]. Fig. **4** displays the trends in U.S. R&D funding (in current dollars) by entities conducting research since 2000.

The business sector is not only the predominant performer of U.S. R&D, but also the primary funder as well, contributing 70 % of U.S. R&D expenditures. In contrast, the Federal Government is the second-largest contributor of U.S. R&D funding, at 22 %. While funding from the business sector largely goes to support R&D by industry, federal funding varies by sector. Additionally, business R&D expenditures have been increasing in recent years, while Federal Government funding has stayed relatively flat, excluding a temporary uptick after the 2008 financial crisis [57].

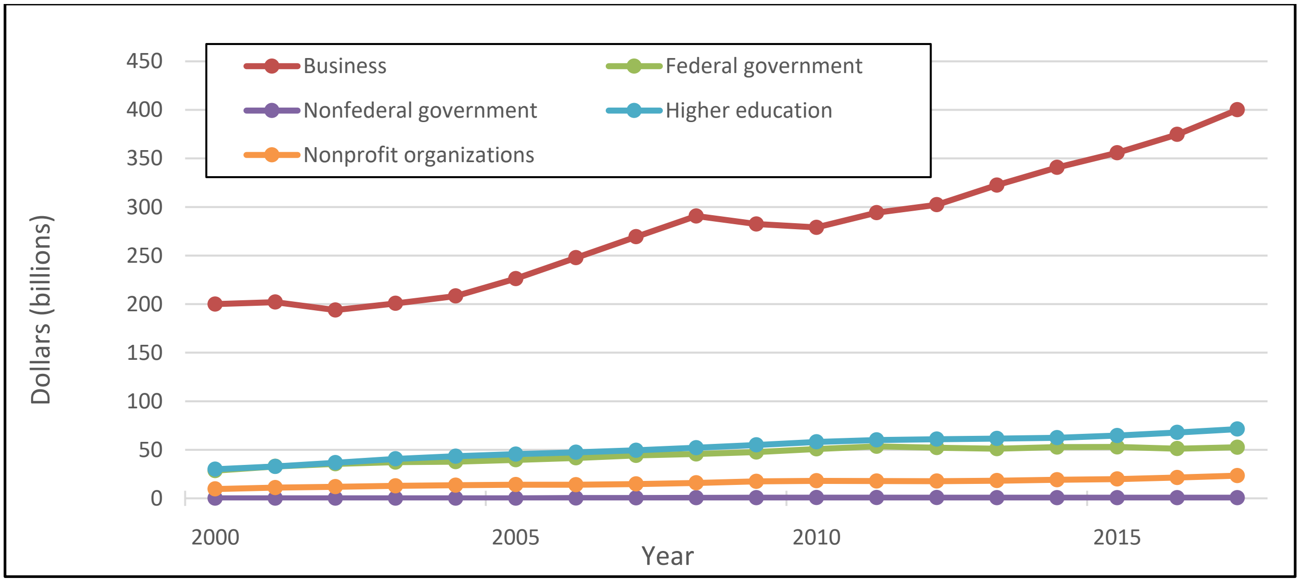


Fig. 4. U.S. R&D by Performing Sector, 2000 to 2017 (in current dollars). [57]

One implication of significant investment in R&D by the business sector is an increased potential for conflicts of interests that introduce bias when the entity performing research stands to profit from the research findings, or has an undisclosed affiliation with the company. The importance of conducting unbiased and fair research by third-party neutral research institutions cannot be overemphasized. Clear policies for disclosure of funding sources and author affiliations can help mitigate these risks. For example, PubMed Central mandates that the disclosure of conflicts of interest on the part of authors and editors must appear on each article [58].

The overall federal obligations for R&D and R&D plant (R&D facilities and fixed equipment) experienced a historical high in 2009 and 2010 owing to the additional funding authorized by the American Recovery and Reinvestment Act (ARRA) of 2009, followed by a decrease and flattening, generally. Figure 5 demonstrates the predominance of business funding in all R&D sectors [57].

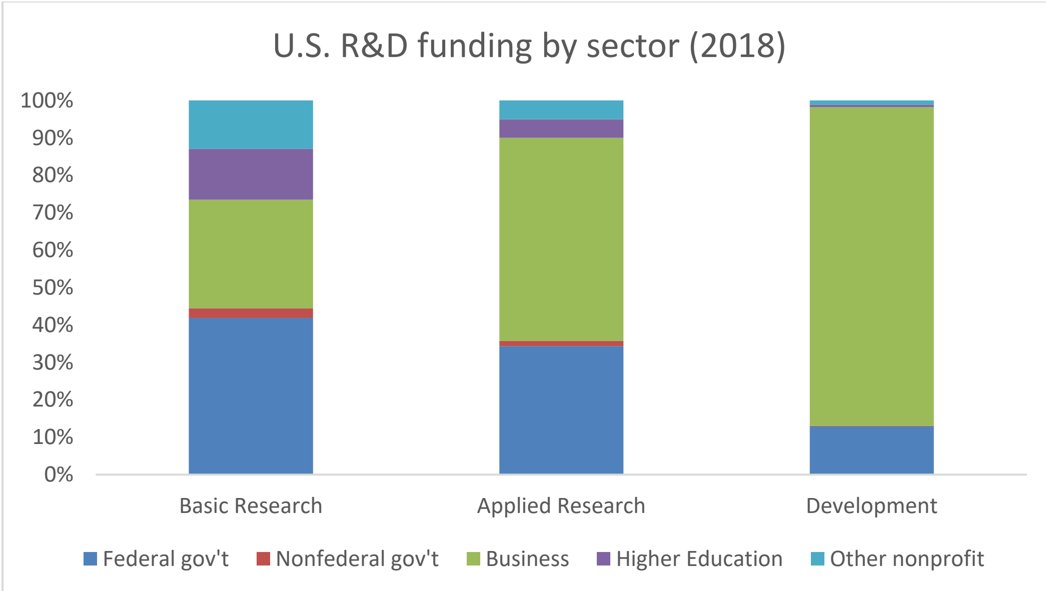


Fig. 5. U.S. R&D funding by sector in 2018. [57]

3.1.2. Innovation

The global and U.S. innovation landscapes are becoming ever more complex and intertwined, as nations seek to transform their R&D expenditures into meaningful benefits for their societies and economies. Knowledge transfer, invention, and innovation have a variety of indicators and measurements. Although patents are certainly not the only measure of innovation, this section focuses on global patenting trends and understanding where the U.S. fits in comparison to other countries.

WIPO (the World Intellectual Property Organization) collects and compiles data from the top patenting offices worldwide that clearly show patenting has grown exponentially in recent years. Although the USPTO (United States Patent and Trademark Office) and Japan Patent Office previously filed the largest number of patents, with the U.S. filing more than Japan of late, it is China that has a skyrocketing number of patent applications worldwide [59]. In order to normalize for the size of a nation's economy, however, it is helpful to portray patents as a ratio to GDP. The normalized WIPO data paints a significantly more concerning picture. In 2018, five countries (South Korea, China, Japan, Germany, and Switzerland) all exceeded the U.S. in patents per $100 billion in GDP (Fig. **6**) [60].

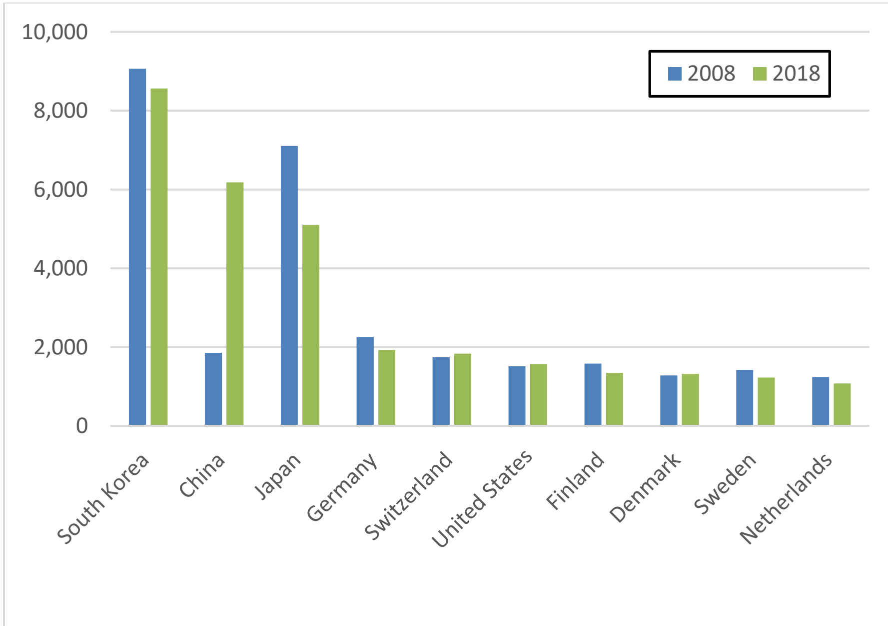


Fig. 6. Patent Applications per $100 Billion GDP in 2008 and 2018. [57]

Although the U.S. may have fewer patents on the worldwide stage, it is still leading in terms of the number of USPTO utility and design patents granted despite the fact that the USPTO grants a little more than half (53 %) of all U.S. patents to international inventors (Table 1).

Table 1. Utility and Design Patents Issued by U.S. Patent and Trademark Office for U.S., China, European Union and South Korea, 2008 - 2018. [57]

	United States		China		European Union		South Korea	
Year	**Utility**	**Design**	**Utility**	**Design**	**Utility**	**Design**	**Utility**	**Design**
2008	77,144	13,598	1,606	1,076	22,031	3,836	7,544	1,196
2009	81,947	11,966	2,043	884	3,557	4,226	8,775	808
2010	107,206	12,539	3,215	935	30,742	3,695	11,669	773
2011	108,091	11,695	3,720	854	30,926	3,330	12,254	897
2012	120,454	12,361	5,359	942	36,239	3,413	13,236	866
2013	133,136	13,194	6,680	941	40,985	3,428	14,556	1,104
2014	144,008	13,320	8,123	926	44,997	3,287	16,529	1,630
2015	140,484	14,194	9,021	1,118	44,589	3,752	17,963	2,229
2016	143,156	15,989	11,439	1,544	44,993	4,141	19,576	2,486
2017	150,392	17,410	14,286	1,864	47,517	4,423	20,815	2,060
2018	142,756	16,490	15,477	2,574	45,934	4,569	19,901	1,976

Recently, China has seen a near 10-fold increase in USPTO patents granted (1600 in 2008 to 15,500 in 2018), although they comprise a fairly small number of USPTO patents overall [60]. In 2018, China had almost three times as many patent filings as the U.S., equaling the combined total of the rest of the top 10 contributors (Fig. 7. U.S. Patent Applications by Country, 2017 and 2018. [61] [61]. While the number of patents filed by a country is not necessarily an indicator of the quality of the R&D production, it does provide a snapshot of the investment the country is making in developing new technologies.

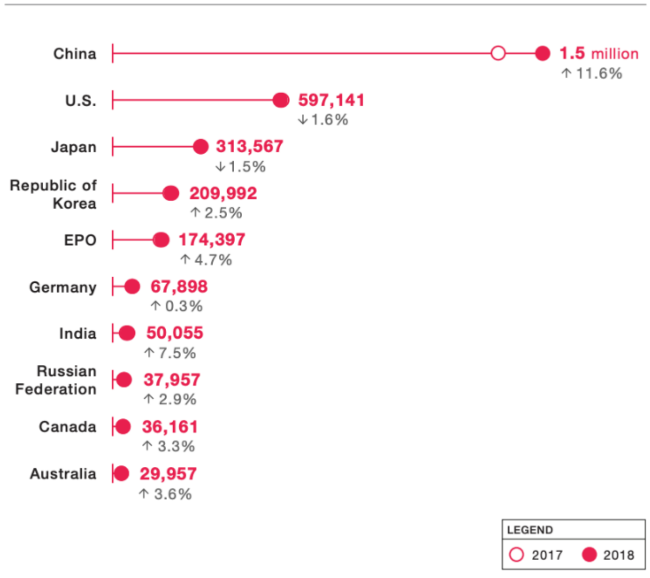


Fig. 7. U.S. Patent Applications by Country, 2017 and 2018. [61]

China's ambitious R&D growth has been paired with an industrial policy focusing on the growth of Chinese research capabilities and companies through multiple approaches including subsidies for international researchers, Chinese industry, technology transfer, and the use of anti-monopoly laws. For example, a 2018 article in the *Washington Post* profiled scientists who were choosing to build their laboratories in China, where they see greater opportunities [62]. Further, we do not yet know the ramifications to the U.S. scientific enterprise from actions by the Trump administration, such as suspension of entry to the U.S. by certain students and researchers from China [63]. The cumulative result of these various international policies is that the U.S. has less opportunity to set strategies around technology development, applications, and regulation around emerging technologies such as advanced communication technologies, quantum information science (QIS), artificial intelligence (AI), and bioengineering.

The COVID-19 pandemic has also potentially impacted the influence of China and the U.S. According to a Pew Research Center survey, 50 % of Americans think that China will emerge from the pandemic with less global influence, while 29 % think the U.S. will have a decreased impact post-pandemic [64]. Some people feel that the U.S. can learn something from how other countries responded to the pandemic, with South Korea and Germany rated as doing a much better job of mitigating the pandemic than the U.S. Other countries have been much faster at developing and rolling out contact tracing to limit viral spread, with varying degrees of privacy concerns. The first app came out of Singapore with at least 25 other countries following suit [65]. The poor response of the U.S. to quickly and effectively respond to the pandemic is concerning for future international discourse, developing strategies, and being a respected world leader, especially since China was reportedly able to acheive containment of their COVID-19 cases within a few months while the U.S. is still struggling to keep infection rates down months into the pandemic.

3.1.3. Student and Workforce Development, Attraction, and Retention

A critical component of the country's S&T workforce is the development of a STEM pipeline for a future workforce. This pipeline is dependent on educational systems, which are compared at three levels: student math and science performance in eighth grade (the end of middle school in the U.S.), the number of undergraduate STEM degrees awarded, and the number of STEM doctoral degrees awarded.

Eighth graders in the U.S. perform in the middle of the pack among developed countries in math and science based on the Trends in International Mathematics and Science Study (TIMSS) results from 2015 [66]. Experts have long recognized that middle school is a critical time for engaging students in S&T subjects; it is also the beginning of a slide where underrepresented groups (marginalized racial and ethnic groups and women) begin to become less involved. As a result, there are many intervention programs in trial to increase engagement in STEM at every stage of education [67]. Additionally, the COVID-19 pandemic has significantly impacted how students engage with STEM as hands-on experience and outreach have all diminished, conferences and science fairs have been canceled, and learning has become mostly virtual. Organizations have had to reevaluate and creatively engage in outreach. However, impacts remain to be seen.

Community colleges granting associate degrees and certificates play a significant role by preparing students for entering the workforce or transitioning to a four-year institution. Over 200,000 associate degrees were awarded in S&T fields and technologies in 2017. The importance of community colleges in preparing the U.S. workforce is emphasized when looking at graduation data from four-year degree granting intuitions. From 2010 to 2017, nearly half (47 %) of students granted STEM degrees had performed some of their studies at a community college and 18 % had earned associate degrees [68].

As of 2016, China more than doubled the number of degrees it granted with a heavy concentration in engineering degrees. China produced 1.7 million first degrees (defined as terminal undergraduate degrees, i.e., bachelors and associates in the U.S.), the EU (with 28 member countries) produced approximately 1 million, and the U.S. followed with nearly 800,000. At the bachelor level, only 6 % of degrees awarded in the U.S. were earned by short-term visa holders. The comparison of doctoral degrees reveals that in 2016, the EU awarded almost 80,000 degrees, the U.S. followed with 40,000, and China with 34,000 in S&T fields. However, these numbers do not tell the whole story. China awarded more doctoral degrees in natural sciences and engineering in 2007 than the U.S. and has continued to do so ever since. In addition, international student representation becomes significant at the doctoral level. In the U.S., 34 % of S&T doctoral students are on short-term visas and approximately 70 % remain in the U.S. for at least five years after earning their degree [68].

The National Science Board (NSB) published a document summarizing the Skilled Technical Workforce focusing on education at all levels, increasing diversity, and recommendations for the future [69]. Skilled technical workers are needed at every level in American industry, and the jobs offered provide individuals with financial independence and economic stability. In the report, the NSB encourages all academic levels to work together and to increase discussion of different technical careers, encouraging more students to study STEM fields. Critical thinking skills and an understanding of how to use technology, programming, and software management are increasingly important in all fields including on manufacturing lines, processing plants, laboratories, and academic institutions. These positions can be made more available to all U.S. students through early career education at elementary levels, with continued education and training, as students progress to secondary education.

3.1.4. Metrology and Standards

NIST is a large NMI with diverse areas of research, and NIST's standing as a leading NMI has long been a part of its core identity. There are approximately 100 NMIs across the world, each focused on the central measurement issues of their geographic region. As part of the International Committee for Weights and Measures (CIPM) Mutual Recognition Arrangement (MRA), NMIs participate in key comparisons, and create detailed lists of calibration and measurement capabilities (CMCs). A CMC is a declaration of an institute's measurement capability that has a known uncertainty. It is available to customers under normal conditions, published in the Key Comparison Database (KCDB). NMIs are grouped into six regional metrology organizations (RMOs): Intra-Africa Metrology System (AFRIMETS); Asia Pacific Metrology Program (APMP); Euro-Asian Cooperation of National Metrological Institutions (COOMET); European Association of National Metrology Institutes (EURAMET); Gulf Association for Metrology (GULFMET); and the Inter-American Metrology System (SIM). Fig. **8** displays the regions [70]. Together with the working groups within the Consultative Committees of the CIPM, RMOs make proposals to the Consultative Committees on key comparison exercises, carry out regional key comparisons, participate in the CIPM, and work together to assure mutual confidence in the validity of calibration and measurement certificates based on the CMCs of each country.

Fig. 8. Regional Metrology Organizations. [70] (this image is reproduced with permission of the BIPM, which retains full internationally protected copyright – Image courtesy of the BIPM)

Throughout the years, NIST has based much of its leadership in the NMI community on the maintenance and expansion of CMCs. However, as other countries have been expanding their CMCs, NIST is beginning to selectively maintain the CMCs that have the greatest impact on the U.S. economy for international trade, commerce, regulatory affairs, and health and safety. The temporary withdrawal of the Joint Research Center (JRC) of the European Union from the CIPM is being carefully tracked and considered by other NMIs.

In addition to the physical standards that NIST and other NMIs produce, there is also significant involvement in the development of consensus documentary standards. The U.S. maintains a strong presence in organizations such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC); however, the participation of other countries including China and India is increasing. As U.S. experts are spread thin, the U.S. influence on international standards decreases. Consequently, without the staff to cover all areas, U.S. interests are not as heavily considered in the standards and a competitive disadvantage may result.

JRC withdraws from CIPM

The Joint Research Center (JRC) representing the European Union has moved to a system where senior management is rotated to new responsibilities. Early in the most recent JRC leadership cycle, a decision was made for JRC to withdraw involvement in the International Committee for Weights and Measures (CIPM) while remaining a signatory on the Mutual Recognition Agreement (MRA). JRC has focused on the production of matrix-based reference materials for use in proficiency testing, harmonization, and method development efforts, but they are not traceable to the SI both because of the nature of the materials. JRC had very few traceable primary standards that industry depends on for safety and/or commerce thus this approach has allowed them to focus on production of materials and programs that directly impact and support the European Union. As a result of the nature of the services and support offered by JRC their reputation as a reference material has not suffered as a result of not participating in the CIPM. However, as of 2021 they have rejoined.

3.2. Implications for NIST

New technologies hold both promise and peril for all countries. In addition to the potential for widespread societal benefits, the rapid pace of technological innovation also has the potential for negative impacts, such as exacerbating existing societal inequalities, causing negative impacts on jobs and labor markets, and opening new cyberattack surfaces with associated vulnerabilities. Additionally, there are important ethical questions that arise. These include concerns over privacy and surveillance potential for technologies such as facial recognition and, more recently, contact tracing applications as a result of COVID-19.

3.2.1. Uncertain Level of Federal Investment

Flat or decreasing levels of federal R&D funding are likely to impact resources available to NIST, especially as a small agency competing for funding with much larger science agencies such as the National Science Foundation (NSF), the National Institutes of Health (NIH), the U.S. Department of Energy (DOE), and the Department of Defense (DOD). Faced with uncertain levels of investment, NIST must continue to reprioritize program areas and projects on a yearly basis, especially in light of changing administration priorities. If NIST decides to address new areas of emerging technologies, it will leave less for existing areas of strength including NIST's core metrology functions, which in turn could adversely impact NIST's ability to maintain long-term core competencies in metrology. Collaborations and establishing reimbursable agreements may become more important for NIST to continue work in certain areas. As industry's national laboratory, there may be room for flexibility through funding of projects by other agencies and industry. The National Metrology Institute of Japan (NMIJ) is a model to consider as approximately 50 % of their funding is from private industry and 50 % from the government.

Beyond uncertain levels of federal R&D funding, one must also consider implications of rising levels of business sector R&D expenditures. As the business sector continues elevated R&D funding, it is critical that NIST maintain credibility with the private sector to promote recommendations and standards for meaningful adoption by industry. NIST must maintain and strengthen existing public-private partnerships and seek out new partnerships to continue to support American competitiveness. Balancing needs of competing stakeholders and partners will continue to pose significant challenges for NIST. As such, NIST must maintain a careful, thoughtful balance between industry's research goals that are driven by short-term profits, against the need for NIST to prioritize research based on the overall good of the U.S. economy and the American public. There are also challenges associated with stretching federal R&D funding by the increased use of public-private partnerships, such as the need for more Cooperative Research and Development Agreements (CRADAs) and similar agreements. This approach may require more NIST staff in acquisitions and agreements management, and/or more efficient processes and workflows to accommodate higher numbers of agreements with external partners.

Another consideration for NIST is the importance of transitioning basic research from the government to industry, as 42 % of funding for all basic research in 2017 was provided by the Federal Government [57]. In addition to technology transfer for more mature research and technologies (already a NIST priority area), NIST must also work to transition basic research into more applied settings. NIST must also translate basic research findings for better understanding, implementation, and eventual adoption by industry. NIST can do more in communicating its research to the general public, helping to raise awareness about the bureau in general, and presenting itself as a trustworthy scientific organization. This may help address the information divide/distrust of science discussed in the previous sections.

3.2.2. Workforce and Collaborations

NIST benefits from an open research environment that fosters close collaboration between talented international researchers and NIST scientists. Changes in immigration policy may have a detrimental effect on the U.S. STEM workforce pipeline unless younger Americans can be enticed to study STEM fields and pursue STEM careers. This shift may limit NIST's access to talent in many emerging R&D areas.

In 2019, there were 894 international guest researchers hosted across all of the NIST organization and campuses, focused primarily in the laboratories. International guest researchers bring new areas of expertise to NIST and provide critical assistance for both R&D and service metrology programs. In addition, NIST commits to working with researchers from other NMIs for the direct transfer of knowledge. Most of these collaborations are related to measurement services. For example, in 2019, the Chemical Sciences Division in the Material Measurement Laboratory hosted several guest researchers from other NMIs, including one from the Instituto

Nacional de Tecnologia Industrial in Argentina, focused on the development of aflatoxin in corn reference materials for food safety. Others from the Instituto Nacional de Metrologia in Brazil worked on improving clinical measurements of iron in blood.

As immigration and visitation rules tighten, NIST is losing out on the ability to leverage the experience and unique skills of these individuals, thus weakening the ability to deliver on its mission. However, NIST has increased its acceptance of student interns from community college level through the graduate school level. For example, the PREP program provides a new, much-needed avenue for the recruitment of top talent on a temporary basis. This program could be employed more broadly across NIST. Under PREP, students develop skills that may significantly contribute to the NIST mission if the student is hired upon graduation. Even under this program, however, many of the students are international and would not be eligible for employment at NIST.

3.2.3. Status as an NMI and Standardization Expert

NIST has maintained its reputation as one of the leading global NMIs. However, as R&D efforts unrelated to metrology dilute the measurement capabilities of NIST through a reallocation of limited funding and other economies invest in their own NMIs, NIST will become less relevant in some critical areas. Because CMCs form the basis of international trade, commerce, and regulatory affairs, they are essential for high-functioning trade relations. The need for new CMCs is apparent; however, participation in CIPM activities that produce CMCs will require NIST to make hard decisions about program engagement.

Similar considerations are necessary as NIST evaluates its standards developing organization (SDO) activities. NIST participates in 112 SDOs, and the bureau’s participation results in significant impacts on international technical standards adoption. With an increasing number of SDOs and activity within those SDOs, it is essential to make strategic decisions about the bureau’s participation to maximize impacts without spreading NIST expertise too thin.

4. Political and Policy Landscape

NIST's budget, workforce, and programmatic priorities are strongly influenced by Congress and the executive branch.

4.1. Landscape

The current landscape and the dynamics between Congress and the White House pose several political and policy-related implications for NIST.

4.1.1. Congressional and Executive Branch Dynamics

There are stark differences of opinion between the two parties and the two chambers of Congress that impact many issues of significance to NIST. Philosophical differences not only between the two major parties but also between factions within each party make bipartisan support and consensus difficult for many issues including: support for fundamental R&D; extent of investment in R&D; the role of government in science and technology; support for initiatives to aid the private sector; and the size of the Federal Government. The extent and nature of U.S. engagement in multi-lateral organizations such as the World Trade Organization (WTO) and World Health Organization (WHO), and the U.S. approach to global trade agreements (multilateral vs. bilateral) have also become partisan topics.

Despite deep-rooted differences, both sides found consensus on issues of national importance: initial relief and stimulus funding in response to the COVID-19 pandemic, U.S. critical infrastructure, national and economic security concerns related to China, and the importance of emerging technologies such as quantum technologies and AI.

Since 2000, there have been five changes of majority leadership in one or both houses of Congress. Coupled with the partisan divides, changes in House or Senate leadership can influence shifts in federal agencies' priorities and planning. The incoming Biden administration is likely to once again influence shifts in federal agencies' priorities and planning.

In recent years, changes have occurred in both the executive and legislative branches that impact S&T policy. Science agencies often take their cue from the White House's Office of Science and Technology Policy (OSTP). At times, OSTP has been short-staffed but it is currently mostly fully staffed and is providing federal agencies more guidance on the administration's priorities and serving as a critical convener of multiple agencies. The House Committee on Commerce, Science, Space, and Technology and the Senate Committee on Commerce, Science, and Transportation maintain oversight of NIST, with appropriations stemming from the House and Senate Committees on Appropriations. In recent years, other congressional committees have also introduced legislation directing NIST's work. For example, NIST's work on fifth-generation (5G) telecommunications technologies has attracted interest from the House Committee on Energy and Commerce [71], and NIST's work on facial recognition technology has recently garnered interest from the House Committee on Homeland Security [72] and the Committee on Oversight and Reform [73].

4.1.2. Federalism

In recent years, the Trump administration has pursued a goal of decreasing federal regulation as documented by Executive Order 13771 in 2017 [74], which directed agencies to identify at least two existing regulations for elimination for every new regulation issued. In response to these changes, some states, like California, have responded by increasing their environmental regulatory activity. This shift is illustrated in the example of fuel economy standards for light vehicles. The Trump administration sought to roll back planned increases in standards; however, states maintained standards locally [75]. A national patchwork of requirements forces manufacturers to tailor product lines to different markets and is considered inefficient.

4.1.3. Fiscal Trends

Federal R&D funding has increased in the past three fiscal years, with FY 2019 allocations estimated to be $151 billion, compared to $133 billion in FY 2017 (in constant 2020 dollars) [76]. While rigorous FY 2020 numbers are not available at the time of writing, Congressional Research Services estimates an 8 % increase in R&D funding (in current dollars) from FY 2019 to FY 2020 for the top seven departments and agencies, which make up over 95 % of federal R&D funding [77].

Expenditures on R&D should be presented within a macro view of federal deficits. The Congressional Budget Office (CBO) estimated deficits would exceed $1 trillion each year beginning in 2022 and that the federal debt would grow to equal 93 % of Gross Domestic Product by 2029 [78]. This estimate was prepared prior to the 2020 Coronavirus Aid, Relief, and Economic Security (CARES) Act, which allocated $2 trillion in response to the COVID-19 pandemic. It also does not include further stimulus bills. For perspective, the CBO estimated that total outlays by the Federal Government in FY 2019 were $4.4 trillion [79].

In recent years, Congress has rarely completed budget allocations prior to the October 1 start of the fiscal year. The delay in Congress passing budgets until after October 1 is likely to continue. Congress has only met the October 1 deadline four times since the current system was put in place in 1977 [80]. This challenging dynamic was highlighted by the 35-day shutdown of the government (from December 2018 to January 2019) when the administration and Congress could not reach an agreement on the FY 2019 budget. Relief came with the passage of the 2019 Bipartisan Budget Agreement, which modified discretionary spending caps imposed by the Budget Control Act of 2011. However, this agreement merely set overall discretionary spending caps. NIST remains dependent on the Appropriations Committees for specific budget appropriations.

4.1.4. Science and Technology Priorities

Administration R&D budget priorities are specified in the annual memo from OMB and OSTP. The most recent memo focused on the FY 2022 planning cycle and highlighted five priorities: American Public Health Security and Innovation, American Leadership in the Industries of the Future and Related Technologies, American Security, American Energy and Environmental Leadership, and American Space Leadership [81]. The administration listed technologies that will power "Industries of the Future" as AI, QIS, advanced communications networks, biotechnology, and advanced manufacturing [82].

The Congressional Research Service outlined a set of science and technology policy issues that could potentially arise during the 116th Congress [83]. This document, which is not meant to be exhaustive, highlights the wide range of issues in which the Federal Government has a stake.

Table 2 lists the ten categories discussed in this report along with examples of key technologies and topics in each category. While most topics have relevance, those that are particularly applicable to NIST are highlighted in bold font.

Table 2. Science and Technology Policy Issues for the 116th Congress. Those topics in **bold font** are particularly relevant to NIST. [84]

Category	Select Technologies and Topics
Overarching S&T Policy Issues	Federal Science & Technology Policymaking **Federal Funding for R&D** Disruptive and Convergent Technology **America COMPETES Act Reauthorization** **Technology Transfer from Federal Labs** **U.S. Science and Engineering Workforce** Tax Incentives for Technological Innovation
Agriculture	Agricultural Biotechnology Cell-Cultured Meat
Biomedical Research and Development	Oversight of Laboratory-Developed Tests **Stem Cells and Regenerative Medicine** **CRISPR: Advanced Genome Editing**
Climate Change Science and Water	Climate Change-Related Science **Greenhouse Gas-Related Technology and RDD&D** Climate Change Infrastructure **S&T for Adaptation and Resilience** Carbon Capture and Sequestration **Water**
Defense	Department of Defense R&D
Energy	Reprocessing of Spent Nuclear Fuel **Advanced Nuclear Energy Technology** **Biofuels** Offshore Energy Development Technologies ITER fusion energy research facility
Homeland Security	Chemical, Biological, Radiological, Nuclear Medical Countermeasures Microbial Pathogens in the Laboratory
Information Technology	**Cybersecurity** **Artificial Intelligence** Broadband Deployment Access to Broadband Networks and Net Neutrality **Deployment of the First Net Network** **Emergency Alerting** **5G Technologies** **The Internet of Things** **Evolving Technology and Law Enforcement** **Quantum Information Science**
Physical and Material Sciences	**Nanotechnology/National Nanotechnology Initiative**
Space	**Commercial Space** Earth-Observing Satellites

4.1.5. Awareness of Role of NIST

It is evident that NIST and the roles it plays are strongly recognized among members of Congress. While many are not familiar with the specifics of NIST work, the scope of activities at NIST, nor its mission, they often hear from constituents about specific activities such as the Cybersecurity Framework, the NIST Privacy Framework, NIST's work in facial recognition, NIST's role in standards, or the Hollings Manufacturing Extension Partnership (MEP). Furthermore, constituents often recommend NIST as an organization to address their specific challenges, even when those challenges fall outside the current expertise of NIST. These recommendations are evidence of NIST's reputation and brand recognition. As such, Congressional leaders and staff often task NIST with responsibilities outside its core mission, or in areas where NIST does not have the relevant expertise or resources. Conversely, there are times when Congressional leaders propose to expand programs in other agencies that overlap with NIST activities. For example, the Endless Frontier Act introduced by Senator Schumer in May 2020 aims to solidify U.S. leadership in scientific and technological innovation by transforming the National Science Foundation into the National Science and Technology Foundation. The transformed agency would lead investments in the discovery, creation, and commercialization of technology fields of the future [85]. The draft legislation calls for the Foundation to "provide funds to other federal research agencies, including the National Institute of Standards and Technology, for intramural or extramural work in the key technology focus areas."

Understandably, some members of Congress do not have an understanding of the voluntary consensus standards process that defines standards activities in the U.S. Furthermore, Congress may not fully comprehend the nuanced role that NIST plays in supporting those processes or the standards development ecosystem as a whole. This misunderstanding manifests itself when Congress requests NIST to take on roles that are inappropriate in the consensus standards process and for the non-regulatory role that NIST strives to maintain, such as developing its own standards, serving as a de facto enforcer of standards, or to engage in testing and certification activities. Congress is increasingly vocal about the need for U.S. leadership in global standards for emerging technology areas such as 5G, QIS, and AI. This recognition is partially brought about as it sees strategic competitor countries become more active in the standards arena, occasionally pushing solutions that have not been thoroughly vetted from a technical perspective or looking to exploit standards development processes to push their national priorities. Since some standards set the course of development for key technologies, Congress recognizes the importance of active engagement by federal staff to ensure the needs of U.S. industry are met.

NIST staff actively engage both the administration and Congress to help enhance their awareness of NIST's roles and responsibilities. At the highest level, the NIST Director maintains strong relationships with senior White House officials in the Executive Office of the President (EOP). Serving as Under Secretary for Standards and Technology, the NIST Director also informs DOC leadership about NIST's capabilities. NIST staff have served detail assignments in the White House OSTP, the National Security Council (NSC), the DOC Office of Policy and Strategic Planning, Congressional subcommittees, and Congressional offices. Additionally, many staff members participate in committees, subcommittees, and working groups within the National Science and Technology Council (NSTC).

4.2. Implications for NIST

The political and policy landscape carries with it significant implications for NIST from a budgetary, workforce, and programmatic perspective. These trends will force NIST to be flexible in pursuing new avenues of research and technology development while evaluating existing programs to ensure that NIST continues to help U.S. industry remain competitive in a global landscape.

4.2.1. Budgetary Perspective

The President's proposed budgets have sent a strong message that the Trump administration's priorities for non-discretionary spending are focused on defense and national security. The administration's proposed budgets for FY 20 and FY 21 requested significant cuts to the NIST scientific and technical programs and also proposed discontinuing the MEP program. In contrast, Congress has maintained the NIST budget at a steadier level from FY 18 through FY 20. In FY 20, the Laboratory Programs received a 4 % increase, ($29.5 million) while the MEP and Manufacturing USA programs received a 4 % ($6 million) and 6 % ($1 million) increase, respectively. Allocations to Construction of Research Facilities (CRF) have fluctuated due to the construction of new buildings. In 2018, $319 million was allocated and included major renovations to Building 245 on the Gaithersburg campus. In other years since FY 16, CRF funding has averaged $113 million per year. The difference between the 2020 President's budget request for NIST ($687 million) and the appropriated budget ($1.0 billion) exemplifies the significant challenges that budgetary uncertainties pose for NIST. While the increase in the FY 20 budget represents positive developments, it is not clear whether such increases can be expected in the future. As with previous years in the Trump administration, the FY 21 Presidential Budget Request included funding levels much lower than that appropriated by Congress in the previous year, requiring NIST to consolidate efforts on its highest priority capabilities and research. All numbers presented here are in current dollars.

The $2 trillion CARES Act of 2020 and subsequent stimulus programs may impact NIST budgets in the future. In the near term, there may be opportunities for NIST to receive additional funds from Congress to support the battle against COVID-19. The initial stimulus primarily supported NIST's extramural programs in manufacturing. Other areas, such as expertise in the bioeconomy, sensing, or resilience, may also be of interest to the administration and Congress. However, stimulus measures will greatly increase the national debt, forcing Congress and the administration to make difficult choices to meet goals of fiscal restraint. This challenge may result in a decrease to NIST's appropriations. Government-wide reductions in discretionary spending and federal employee benefits may occur. In light of the national debt, NIST will need to prepare justification for its budget and its returns to the American public.

Congressional delays in passing a budget and continuing resolution(s) create challenging planning processes for NIST staff. They are significantly limited in making definitive, long-term spending plans and must operate cautiously until budgets are appropriated.

4.2.2. Workforce

Budgetary guidance from the administration, particularly when planning for significant reductions, requires managers to identify programs for reduction or elimination. Such deliberations, even if not acted upon in final congressional appropriations, have adverse impacts on staff resources, productivity, and morale. Volatile funding conditions create challenges in staff recruitment and retention, jeopardizing NIST's ability to maintain a robust talent pool. While much of the laboratory staff have come to understand the funding process, newer employees have reacted to Presidential budget requests eliminating their programs with questions about seeking employment elsewhere. NIST leaders must continue to communicate the budget process and program priorities to staff to ensure that programs can be effectively carried out if Congress maintains appropriations at steady levels, as it has done in recent years.

The CARES Act may also have implications on the NIST workforce. Response to the COVID-19 pandemic may force NIST to curtail existing activities, allowing more resources to be placed in accordance with stimulus package provisions. Staff may be forced to cease activities in order to address more pressing issues. Furthermore, any budgetary deficits resulting from the CARES Act may force future administrations and Congresses to decrease discretionary spending through cuts in the federal workforce or federal employee benefits. These steps may affect staff recruitment and retention.

4.2.3. Programmatic Perspective

The close balance of party leadership in both houses of Congress and the polarization expressed in the previous section will require NIST to be flexible in responding to changing priorities from the administration and Congress. The breadth of NIST activities bodes well moving forward, as NIST addresses key problems that are generally supported by both parties. While responding to priorities, NIST must also maintain, when appropriate, legacy efforts that still have significant support from stakeholders in industries that are not part of those priorities. However, the emergence of critical needs will force NIST to make difficult decisions about ending legacy programs in support of the new priorities.

While NIST maintains strong support in Congress, the lack of understanding of NIST's role and how NIST operates raises risks of it being tasked to carry out duties that are beyond its expertise. For example, Congressional leaders have sought to assign NIST a quasi-enforcement role relating to cybersecurity. Cases like this one, where Congress perceives a lack of progress by industry on specific issues or the inability of other agencies to deliver, may result in NIST being tasked with an assignment that is not suited to its core competencies of measurement science, rigorous traceability, and development and use of standards. NIST is reputed for its scientific rigor and discipline, which frequently requires more time than Congress can afford when it faces the need for rapid action. To avoid such situations, NIST must continue to inform Congress of its unique capabilities.

Raising awareness about NIST's programs and expertise requires considerable time and effort to ensure that administration leaders, congressional members, and their staff understand what NIST can deliver. A strategic approach to raising NIST awareness should include consideration of NIST representation in key administration offices such as the Office of the U.S. Trade Representative (USTR), OSTP, NSC, National Economic Council (NEC), or DOC Secretary's offices, or Congressional committees. Creating opportunities for developmental or detail assignments for NIST staff would benefit both the organization and the individual. A NIST employee with strong technical foundations, an interest in policy, and good communication skills can gain valuable experience while providing significant value to NIST within these offices. Incentives may help sway those NIST staff who are discouraged from taking on such assignments. Additionally, NIST could consider ways to leverage the experience gained by the employee upon their return. At present, staff who serve on details typically go back to their previous roles in the laboratories. For those who may have found that their skills and interests better match policy-related efforts, the best career opportunities may require them to leave NIST even though they could likely serve NIST in some capacity with their newfound knowledge and experience.

As the Federal Government seeks to reduce regulations while some states try to fill a perceived gap created when those regulations or standards are relaxed, NIST will need to be mindful of situations where industry faces local challenges in meeting standards or regulations. Such a situation will necessitate NIST staff to be tuned in to state-level activities that will impact industries that they serve.

Current efforts at NIST are well-aligned with priorities pursued by the Trump administration. NIST's focus areas on advanced manufacturing, AI, disaster resilience, engineering biology, Internet of Things (IoT), and QIS closely align with the priorities expressed in the Fiscal Year 2021 and 2022 administration Research and Development Budget Priorities memos. These and other emerging areas, where Congress and the administration seek to establish or maintain U.S. leadership and economic competitiveness, are opportunities to grow NIST programs. Topic areas include infrastructure, machine learning, advanced communication, and operations in a zero-trust environment. Growing these programs, along with other high-profile programs, could require NIST to take on additional risk, in the form of an initial financial burden, or having to curtail existing programs. NIST must also be aware of the Endless Frontier Act. Its passage may complicate the technology-advancing leadership position that NIST enjoys within the Federal Government. If the bill passes, NIST will need to work with the newly formed National Science and Technology Foundation to ensure that activities are complementary and not duplicative.

Congress and the administration's interest in the U.S. approach to standardization meshes well with the core competencies of NIST. As such, it presents an opportunity for NIST to utilize its skills in technology and standards coordination. The emerging areas of AI, IoT, and autonomous devices are of particular interest to a broad range of Congressional committees that do not conduct oversight of NIST, and the EOP offices that do not traditionally engage with NIST. To keep these groups informed, NIST needs to proactively engage with them. Doing so will help committee and EOP staff understand how NIST can help them achieve their goals.

As the country deals with the COVID-19 pandemic, NIST faces questions regarding its potential role in mitigating impacts to health, as well as helping in the economic recovery resulting from multiple shutdowns in response to the pandemic. With its mission to promote U.S. innovation and industrial competitiveness, NIST may need to aim its resources at finding innovative ways, both technological and social, to assist industry. Specifically, NIST can help industry confront a new reality that involves social distancing within the workplace.

5. Technology and Science Landscape

Various influential technologies are currently in the mainstream but still require further advancement. These technologies form the foundation for future innovation across the science and technology enterprise. Ten technology drivers are highlighted in this section, from cyber and food security to sustainable innovations and advanced manufacturing. The table below summarizes each theme, areas of overlap, and implications for NIST. The table is then followed by detailed descriptions of each topic.

Table 3. Summary of Technology Drivers

Technology Driver	Overlaps With:	Encompasses	Implications for NIST
Security	Privacy, Data	• Cybersecurity: securing the digital space to lessen cyber attacks (including malware/ransomware and utilities) and be better prepared when they happen • Food security: reliable access to food and food safety along global supply chains	• Cybersecurity Framework • Quantum-resistant cryptography tools • Development of agricultural reference materials & adoption of international food standards
Privacy	Security, Data	• Managing privacy risks and maintaining trust • Technological changes and societal shifts impact on the meaning of privacy	• NIST Privacy Framework updates and collaboration with industry to address needs
Sustainable Innovations	Data, Security, Privacy	• Datasets to improve water and energy usage • R&D support for new energy technologies • Smart grid optimization • Customizable life-cycle assessments • Equity accessing smart systems	• Measurements and standards for international adoption • Addressing smart city challenges including measurement needs and interoperability guidelines
Health	Data, Security, Privacy	• Precision medicine • Digital public health (e.g., cloud-based patient data) • New ways to access medical information including wearable devices and at-home testing kits	• Reference materials and standards for genomic testing • Biological sensor development and manufacturing automation for screening and scale-up
Data	Security, Privacy	• Increasing data production due to Internet of Things • Securing and protecting each aspect of data life cycle	• Big Data Interoperability Framework • Cybersecurity expertise • AI training and standards • Standard Reference Data
Drones & Autonomous Vehicles	AM, Security, Data, Privacy	• Drones in hazardous environments and AI applications • LiDAR for self-driving cars	• Fundamental research, documentary standards for interoperability, performance characteristics, and data security • Sensors and sensor networks
Advanced Manufacturing (AM)	Data, Security, Privacy	• Application of machine learning for smart and additive manufacturing • New robotics applications	• Standards and framework for AM processes • Development of sensor technologies and standards for industrial robots

		• Digital twin technology • Blockchain	• Interoperability in Industrial Internet of Things
Human Augmentation	Health, Security, Data, Privacy, AM	• Integrated sensors to monitor health including gene editing tool CRISPR • Bionics and prosthetics to aid workers, especially in sectors like manufacturing	• Standards to test safety and performance of new technologies • Neutral party to engage with industry
5G & Next Generation Communication	Security, Data, Privacy	• Rollout of 5G networks and international competition • New technology capabilities needed for 5G application	• 5G mm Wave Channel Model Alliance to set standards and best practices • Measurement challenges for spectrum sharing and wireless interference
Space	AM, Data, Security	• Commercial space market private investment over the last decade • Space debris and need for space trafficking • Additive manufacturing and materials development needed for research and survival in space	• Development of aerospace materials • Sensors and standards for space safety and satellite constellations

5.1. Security

5.1.1. Background

The notion of "securing our digital experience" refers to users and providers implementing good digital practices to reduce the frequency and impact of attacks (such as malware) and quicken recovery when attacks happen. Whether it is the inadvertent release of personal information, unintended access to secure systems, botnet denial-of-service attacks, or insider threats, there is a need to improve and prepare for the security issues of tomorrow. Some of the more high profile online security issues include [86]: (1) the 2013 hack of Yahoo's 3 billion accounts as announced by Verizon; (2) the poor security of First American Financial Corp. that allowed public access to over 885 million records containing personal information in 2019; (3) the 2019 exposure of 540 million records including user login information by Facebook; (4) the 2018 Marriott hack that exposed the personal information of up to 500 million people; and (5) the security breaches at the Office of Personnel Management discovered in 2014 and 2015 that exposed sensitive information of 22.1 million federal employees and their friends and families to Chinese hackers [87].

As more of the world transitions online, cybersecurity threats have become an increasingly pressing issue. With the rollout of 5G and the acceleration of network-connected IoT devices, networks will become more vulnerable because not all devices and cloud solutions are properly protected. Additionally, the number of malware attacks and phishing schemes will only increase as our communication methods become weaponized and cybercriminals try to prey on unknowing consumers. In the first half of 2019, there was a 50 % increase in mobile banking malware compared to 2018 [88]. Over 58.5 billion robocalls were made in 2019, up 22 % from the previous year. The Federal Communications Commission (FCC) introduced new policies and actions to help crack down on these scam calls and President Trump signed the Pallone-Thune Telephone Robocall Abuse Criminal Enforcement and Deterrence (TRACED) Act into law at the end of 2019. The TRACED Act requires phone companies to block robocalls free of charge to customers [89]. While AI can be used to quickly identify threats and initiate a security response to control or block attacks, it can also be used to find and take advantage of system vulnerabilities. Finally, if a cyber "cold war" between the U.S. and China intensifies, and each country competes for technology development while decoupling their economies from one another, cybersecurity attacks may be used as proxy attacks between smaller countries, orchestrated by larger nations wishing to expand their influence [90].

Utilities and other critical infrastructure also suffer from cyberattacks. In 2019, the U.S. electric grid was targeted; however, it did not sustain any power failures. South African utility companies on the other hand, suffered a ransomware attack that left some residents without power [90]. Also vulnerable is the satellite-based Global Positioning System (GPS). It supports sectors including finance, electricity, agriculture, and telecommunications. GPS enables applications that have increased global productivity and efficiency, while also providing benefits for the environment and public health. In the United States alone, GPS generated roughly $1.4 trillion in economic benefits since it was made available for public use in the 1980s. A recent report estimated that a GPS outage would have an impact of $1 billion per day, and up to $1.5 billion per day, if the outage was during the critical planting months of April and May. This estimate emphasizes the importance of resilient position, navigation, and timing (PNT) systems [91]. In addition to these systems, future security concerns may come from new private satellites, such as those owned by SpaceX. Their reach and impacts have yet to be determined.

Security does not only include the cyber and physical networks – it also encompasses the world's food supply. According to the United States Aid for International Development (USAID), food security means "having, at all times, both physical and economic access to sufficient food to meet dietary needs for a productive and healthy life" [92]. One of the United Nations' (UN) 17 Sustainable Development Goals for 2030 is to end hunger and achieve food security and improved nutrition [93]. Globally, over 800 million people feel the effects of food insecurity. This equates to 1 in 9 people facing hunger. In Africa, this number increases to 1 in 5 people. In the U.S., about 15 million people were food insecure in 2018 [94]. Despite decades of progress, world hunger increased from 2015 to 2018 due to factors including conflict, climate change, and economic marginalization [95]. Measures such as economic and social policies that counteract the effects of a negative economy can also help reduce the rate of global hunger. They include maintaining essential programs and increasing partnerships between farmers in order to encourage sustainable and resilient farming practices. As the global population trends towards 9 billion people (by 2050), actions to address this issue become increasingly important [96].

Tied in with food security is food safety. If the available food is not safe to consume, human health and longevity are adversely impacted. It is estimated that 600 million people get sick each year after consuming contaminated food, with children under the age of five disproportionately affected [97]. Safe and nutritious food not only contributes to food security that keeps the population healthy, but also supports trade, the economy, and sustainable development. As the food supply chain becomes more globalized and consumers demand a greater variety of food, it is imperative that every component of the world's supply chain promotes food safety. The Centers for Disease Control (CDC) estimates that 1 in 6 Americans get sick from contaminated foods or beverages each year and the resulting foodborne illnesses cost over $15.6 billion per year [98]. The U.S. Food and Drug Administration (FDA) reported 1246 food recalls between January 2017 and March 2020, either due to the known or potential presence of microbial contamination or undeclared allergens [99]. Examples of contaminated food include melamine-contaminated infant formula in 2008 that affected 300,000 infants and killed 6 in China [97] and the 2018 outbreak of romaine lettuce containing *E. coli* that spread to 36 states and resulted in 5 deaths [100].

A common thread for security issues is securing supply chains. Even before the COVID-19 pandemic, securing the supply chain was an issue of national security; the pandemic has only amplified this issue. With an increasingly global supply chain, disruptions in one section of the supply chain have drastic ramifications down the line. The U.S. has been working proactively to prevent vulnerabilities in the supply chain and reduce reliance on international suppliers, rather than acting only when breaches and vulnerabilities arise. As mentioned earlier in this section, the rise of advanced technologies like 5G and IoT-connected devices will only increase the prevalence and possibility of cybersecurity attacks. This risk extends to the supply chain as well; therefore, public and private sectors must both exercise risk awareness. Additionally, since supply chains are multi-branched rather than linear, there are myriad opportunities for products to be modified before they reach the U.S. Cybersecurity attacks can facilitate espionage, compromise federal information technology systems, or cause products to perform below expectations or fail [101].

Forgeries and product authenticity are also a major concern [101]. The 2018 Global Brand Counterfeiting Report estimated that global counterfeiting would reach 1.82 trillion dollars in 2020. This activity includes counterfeiting across all industries, from defense equipment to watches. About 80 % of counterfeits come from China. But as supply chains shift out of China, counterfeiting rates are increasing in other Asian countries and the Middle East. It is estimated that only 3 % to 5 % of cargo shipments coming into the U.S., selected by a risk algorithm or random sampling, are examined by Customs and Border Control. Therefore, many counterfeits enter the domestic market. Additionally, it is increasingly difficult to detect counterfeit products [102]. To illustrate the seriousness of the issue, during a pandemic, markets that are flooded with fake equipment, medicine, and PPE can be dangerous and actually impede efforts to contain viral spread. In this instance, counterfeiting may have serious health implications.

5.1.2. Implications for NIST

NIST is respected for its role in securing non-classified federal systems [103] and helping organizations manage their cybersecurity risk through the development and ongoing enhancements to the NIST Cybersecurity Framework (CSF) [104]. The first updated version of the CSF was published in April 2018 and it is likely that NIST's ownership of, and thus responsibilities to maintain, improve, and expand the CSF, will continue for years to come. This cybersecurity knowledge can also be expanded to securing cryptocurrencies such as Bitcoin. Looking forward, the promise of quantum technologies requires vigilance in developing quantum-resistant cryptography to protect systems of the future. Development of encryption tools is already underway with the help of NIST expertise [105]. Regarding the supply chain, the current controls developed by NIST extend to "high-impact" federal information systems. Expanding these controls to broader supply chain systems, including the private sector, could improve risk management of potential threats [101]. NIST's work on blockchain in the manufacturing supply chain can be applied more broadly to help secure the global pipeline in this area [106]. Being able to trace each component of a product at all stages of the pipeline increases transparency and trustworthiness of the supplier while decreasing counterfeit goods.

In February 2020, the White House issued an Executive Order on *Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services* to ensure that the nation's critical infrastructure is resilient to disruptions in GPS or PNT sources [107]. NIST is called upon to help organizations make risk-informed decisions on the use of these services and has the capability to offer an alternative time source over optical fiber lines [108]. As vulnerabilities in PNT systems are further explored in the future, NIST will continue to be an important player in developing and updating best practices for securing those capabilities.

As the global food supply chain becomes more complex, key stakeholders have a vital need for standards to test product authenticity and to identify the presence of contaminants. The regulations on food products vary from country to country, complicating the decentralized supply chain and making it difficult to assess the safety of certain foods. As a leader in standards development, NIST is well poised to offer suitable reference materials and/or data repositories needed for testing and can work with international standards bodies to improve standards adoption. NIST can also partner with the food industry and manufacturers to develop innovative diagnostic techniques, next-generation measurement capabilities, software, and standards that further improve food safety, quality control, and supply chain efficiency.

As climate change affects the viability of farmland, new reference materials will be needed, and demands for certain types of import/export foods will materialize. Also, climate change will spawn new chemical or biological contaminants that require identification and mitigation. NIST can help with development and implementation of new standards, while building partnerships between regulatory bodies, and encouraging the widespread development, adoption, and implementation of testing that supports global trade.

5.2. Privacy

5.2.1. Background

As technological devices become more ubiquitous, individuals and organizations may not be fully aware of privacy issues resulting from the interactions of people, systems, products, and services [43]. People typically interpret privacy in terms of controlling information. More broadly, however, privacy relates to other human values such as trust, a sense of agency, identity, respect, and dignity [109]. Failure to manage privacy risks can have adverse consequences for both individuals and society [110]. Increasingly, as society becomes more dependent on technology, a tradeoff is emerging between convenience and privacy and some approach to the management of that risk is needed [111].

There are several technological trends concerning privacy: hardware that increases the amount of information that can be gathered and stored, networks that increase the connectedness of hardware, software that is used to extract information from local or network data; and techniques that use information to create additional data about an individual’s pattern of behavior (data profiling). In addition to technological changes, societal shifts and exogenous shocks will affect notions, perceptions, and expectations of privacy. Societal shifts refer to the evolutionary changes and transformations of institutions, practices, and behavior through their routine use. Exogenous shocks refer to events and emergent concerns that transform the debates surrounding privacy in a very short time [112]. Recent examples of shifts and shocks include the expanded use of social media and the U.S. government’s attempted ban of the Chinese app TikTok.

5.2.2. Implications for NIST

Governments are in the process of passing and implementing new laws to ensure higher standards for software security and data privacy. In 2018, California became the first U.S. state to enact basic standards for software used in IoT. The proposed legislation on privacy and security at the state level, along with a host of proposals at the federal level, would raise the penalties for harms caused by privacy or security failures [113]. At the moment, however, most firms are not fully equipped to sell software that protects the privacy of its users. This is due to high costs, low incentives, and a lack of consumer demand.

Firms are becoming increasingly open to sharing data because it can improve operations and create new opportunities. Even the most noble efforts create data privacy concerns for parties involved. For example, GlaxoSmithKline (GSK) and 23andMe formed a partnership giving GSK access to 23andMe's genome database to be used for researching diseases and developing cures. Although 23andMe claims to be following strict data-sharing guidelines, privacy still remains a concern [114]. As customer demand and regulations increase, companies will have to demonstrate that security and privacy controls are not simply an afterthought, but a core requirement [113]. NIST must prepare to respond quickly to the needs of industry, as firms and organizations adopt the NIST Privacy Framework [114].

5.3. Sustainable Innovations

5.3.1. Background

Providing life's essentials (i.e., food, water, and energy) for the world's growing population is a major challenge. Doing so in a responsible manner is an even bigger challenge. Feeding a growing global population, while minimizing impacts on water, soil, and climate, poses substantial challenges over the next several decades [115]. The recent explosion in the availability of data presents many opportunities to improve the resilience and efficiency of food and agricultural production. To inform decisions effectively, data analysis must account for multiple factors. For example, understanding yields requires analysis of plant genetics, farm management practices, local environmental conditions, and socioeconomic factors over a range of spatial and temporal scales. Data standards and tools that can manipulate and analyze such large and complex datasets are needed to facilitate these advances [116].

5.3.2. Water

Global water use is anticipated to increase 55 % by 2055, with the largest increases in Brazil, China, India, and Russia [117]. At the same time, surface water and groundwater resources are increasingly stressed. Fewer conventional sources of water, such as dams and reservoirs, are being constructed in part because of increasing awareness of their environmental impacts. Thus, alternative means of supplying water will be needed [115]. These methods include desalination, distillation, and reverse osmosis, as well as the recovery and reuse of discarded water.

5.3.3. Energy

Access to energy is recognized as a basic human need. UN Sustainable Development Goal 7 is to "ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030 [118]. For the foreseeable future, the usage of sustainable energy is predicted to increase; however, current priorities and decisions will determine how future societies will benefit. The sustainable energy innovation challenge requires a systemic and multi-stakeholder approach to help bring a broader set of nascent technologies to technical and commercial maturity. Public funding programs will provide early support to these nascent technology areas in the form of research, development, and demonstration (RD&D), research infrastructure, and interdisciplinary and multi-stakeholder collaboration. Despite a recent surge in investments, and the evolution of enabling policy instruments, clean energy RD&D funding levels lag compared to other sectors, while significant barriers to innovation remain [1].

One of the keys to smart energy is possessing the capacity to optimize grid operations. Electrical devices must be able to communicate their operating status, collect information on grid conditions, and respond in ways that most benefit their owners and the grid network. The future of renewable energy is also digital. For example, a digital wind farm will be able to collect, visualize, and analyze unit- and site-level data. Through the constant collection of this data a predictive model is built and data is turned into actionable insights. These models will serve as the basis for a new suite of applications that allow wind farm operators to optimize maintenance strategies, improve reliability and availability, and increase annual energy production [1].

5.3.4. Waste Management

In nature, waste is a resource. One organism's waste is repurposed to sustain another. Since the Industrial Revolution, human society has adopted a more linear model [115]. An analysis of five high-income countries found that one-half to three-quarters of annual resource inputs are returned to the environment as waste within a year [119]. Design is the stage that most influences the types and amounts of waste or pollution that will be generated. At the design stage, engineers can help select and evaluate the characteristics of the final outcomes. They consider material, chemical, and energy inputs; effectiveness and efficiency; aesthetics and form; and specifications such as quality, safety, and performance. In the development of new systems, this stage is ideal for innovation and creativity. It represents a key opportunity to integrate environmental goals into the specifications of the products or processes [115]. Further, access to versatile and customizable life-cycle assessments and technoeconomic analysis models is needed to help small and medium-sized manufacturers evaluate their environmental impact.

5.3.5. Urbanization

The future is increasingly urban. Cities will absorb almost all of the world's projected population growth in the next three decades. Massive concentrated population growth is likely to further compound many of the current problems that cities face (e.g., large, dense informal settlements in low- and middle-income countries). Increased human contact with domestic animals and wildlife in these dense settings also heightens the risk of diseases with pandemic potential as was seen in the COVID-19 pandemic in 2019-2020. The scale and structure of cities offer unique opportunities to improve quality of life and equitably address many of the grand challenges including climate change adaptation, pollution, waste, sustainable food, water, and energy supplies. Improvements in efficiency can be gained through "smart" technologies that leverage sensing technology, data, connectivity, AI, and participatory governance [115]. Unfortunately, smart systems that predict and monitor urban infrastructure are few and mostly limited to higher-income countries. Finally, innovative solutions, technologies, and policies are needed to improve public health in low-income settings.

5.3.6. Implications for NIST

Firms are working to develop and deploy innovative energy solutions within the constraints of current policies. There is a clear role that NIST can play because measurements and standards are critical for both policy development and evaluation. Access to accurate, internationally recognized measurements and standards is required for the implementation of sustainable solutions and climate change-related policies throughout around the globe. NIST's roles in security, sensors, materials, engineering, best practices, guidelines, and standards are all critical to the success of sustainable innovations.

In addition to technology standards, data standards and tools that can manipulate and analyze large and complex datasets are needed to facilitate the advances mentioned above. For example, the emerging area of smart cities represents the importance and growth of systems engineering, communications, and software/algorithms. The goal is to design and deploy IoT solutions that are replicable, scalable, sustainable, and supported by the identification and adoption of a consensus framework for smart city technologies. NIST scientists and engineers will play important roles in addressing many smart city challenges, especially those that leverage NIST's expertise and leadership in standards and interoperability, measurement and metrics, and testing and certification. Additionally, NIST should expect inquiries about how standards and standardized approaches can help increase user confidence in these technologies.

5.4. Health

5.4.1. Background

One of the most fascinating aspects of public health is the way it changes over time. Health concerns in the early part of the 20th century are unlike health concerns of the 21st century. However, for those studying and working in the field, the goals are similar: better health for more people. Most of the top 10 emerging technologies highlighted by the World Economic Forum in 2018 were related to healthcare. They included augmented reality, personalized medicine, AI-led molecular design, more capable digital helpers, implantable drug-making cells, gene drives, plasmonic materials, and electroceuticals [120]. In 2019, almost half of the Forum's top 10 were health related and included disordered proteins as drug targets, DNA data storage, miniature device lenses, and collaborative telepresence [121].

Precision medicine considers each person's individual variability in genes, environment, and lifestyle. It could change every aspect of modern healthcare; however, many of the technologies needed have yet to be developed, or are in the early stages of development. Though nascent, the precision medicine industry is evolving into a lucrative enterprise and is changing how medical professionals treat diseases, especially cancers. The global market is expected to reach $88.6 billion by 2022 at a compound annual growth rate (CAGR) of 12.5 % from 2015 to 2022 [122].

Digital public health (DPH) is a re-imagining of the public health process that blends established wisdom with new digital concepts and tools and leverages a key aspect: data surveillance. As the data revolution changes healthcare into a data-driven industry, data collection systems have made public health surveillance increasingly complex. While it may be tempting to believe that technology can mitigate health threats, human expertise is still an essential part of data interpretation, disease diagnosis, and public health communication. Therefore, in order to tackle the most difficult health issues, crowdsourcing can be used for innovative solutions, information dissemination, and expert engagement. Hackathons and similar contests are an example of this approach [123].

The healthcare industry has access to a wealth of data from wearable devices and to online analytics tools. Mobile phones and cloud-based solutions can store and provide access to health information. Personal devices allow individuals to continuously monitor lifestyle behaviors, such as diet and physical activity, while providing early diagnostics and treatment compliance. Mobile phones support virtual consultations, remote diagnostics, and monitoring, and can also manage health claims and prescriptions.

When individual data are aggregated, cloud-based solutions are useful “medical instruments” for doctors and healthcare workers. Using data and analytics tools, doctors can determine what factors keep people healthy, rather than determining what makes them unhealthy [124]. Machine learning algorithms are used to conduct genomic sequencing and to analyze vast amounts of data collected from patients and healthcare institutions. AI techniques are used in precision medicine to understand genotypes and phenotypes in existing diseases, improve the quality of patient care, rapidly and accurately interpret images, enable cost-effectiveness and improved workflows, and reduce readmission and mortality rates. At a time when the U.S. healthcare system operates at high costs and varying levels of care, the integration of AI may prove critical [125].

In addition to patients processing their own data through AI, the number of people comfortable with using at-home medical tests is increasing. As of 2019, more than 26 million people have taken DNA tests from companies to get their genetic information and health reports; this number is expected to hit 100 million within two years [126]. At-home flu tests are in development and the latest Apple Watch contains an electrocardiogram app that alerts users when irregular heartbeats are detected [127]. At-home tests are relatively inexpensive and can improve health access to rural communities. As more consumers adopt digital medicine, the use of telehealth appointments may also increase, especially after its expanded role during the COVID-19 pandemic.

The flow of additional data creates risks, including the potential for healthcare providers becoming high-value targets in cyber-attacks. This may lead to higher costs associated with cybersecurity. In 2017, a global cyber-attack crippled the National Health System (NHS) in the United Kingdom (UK), holding computer systems hostage for bitcoin ransom [128]. Along with preventing health professionals from accessing information, vulnerable instruments can also be hacked for patient data. Therefore, all IoT-enabled instruments must be secured properly.

5.4.2. Implications for NIST

Many of the issues raised above can benefit from a measurement infrastructure that protects biomedical research data and provides confidence in clinical decision-making. As such, NIST can provide the necessary analytical tools and associated reference data/materials.

NIST’s current activities put the agency in a position to make immediate contributions in several areas. For instance, NIST is currently working to address inconsistent standards for genomic tests. Current genomic diagnostic tests are evaluated for their “clinical utility,” a metric that is neither clear nor predictable. Objective and reliable standards for the evaluation processes are needed in order for genomic tests to be broadly accepted. Future advances in molecular profiling technology and analysis, combined with genetic clinical information, promise unprecedented advances in precision medicine. However, they will require precision measurements, an area in which NIST excels. Data privacy policies and the cybersecurity of medical technologies are also areas that NIST can help.

As medicine transitions to precision medicine, NIST can contribute to sensor development required for research in devices that track individual health and monitor target molecules. NIST's manufacturing and research expertise is well-positioned to develop automation methods for high-throughput screening, as well as new methods for manufacturing the scale up of gene therapies.

Another way NIST can play a role is through the development of explainable AI (XAI). A recent *Science* article highlighted racial bias in a widely used medical algorithm that determined which patients needed more care [129]. XAI would help users understand the AI's decisions, why and how the AI produced certain results, and identify the AI's errors or bias [130]. The work NIST has done with identifying bias in facial recognition, along with its expertise in machine learning, makes NIST a uniquely qualified resource. Assisting in the development of XAI will contribute to trustworthiness in AI, which is one of the tasks assigned to NIST in Executive Order 13859 (Maintaining American Leadership in AI).

5.5. Data

5.5.1. Background

Data are constantly being generated and collected. Every day, 500 million tweets are posted, 5 billion searches are conducted, and 294 billion emails are sent. It is estimated that by 2025, 463 exabytes of data will be created every day [131]. The entire digital universe is projected to reach 44 zettabytes by 2020 [132], which equates to 5600 GB of data for every person on Earth. A primary driver for the amount of data produced over the last few years has been IoT-connected smart devices. With this influx of data comes certain challenges and considerations. They include the regulation of data access and storage platforms and the analysis and use of datasets.

The 2010s were dominated by the rise of Big Data, characterized as data sets too large to be analyzed using traditional methods. The next decade will shift to real-time data consumption through IoT devices that are analyzed by intelligent applications [133]. The data lifecycle starts with the generation of data coming from sources ranging from wearable health sensors to complex scientific machines. Much of these data contains personal information that must be protected and only discoverable to those with approval. FAIR data principles [134] state that it is especially important for biomedical data to be findable, accessible, interoperable, and reusable; these principles must be applied in an ethical and long-term way [135]. Inherent in this concept are notions of trust between consumers and the firms holding consumer data (sometimes without their knowledge). Customers expect transparency from companies regarding data practices, how companies prevent cyberattacks, and how companies address internal misuse of data.

When data is processed before storage, it can be cleaned up, formatted, or compressed for efficient storage, and/or encryption. As digital infrastructure evolves, thought must be put into how to store and manage data long-term in order to prevent file corruption or loss. Not all data repositories are maintained or have equitable access, which are important factors when choosing where to store published data that might be used by other researchers. Risk areas for data storage include: the geographic location of data; the file integrity after transfer; the presence of metadata; and copies available in alternate locations. Cloud computing is a popular choice for storing big data offsite because it does not require active user management that slows down processing time. Edge computing has developed as a response to exponential IoT use, pushing data centers to the edge of a network and allowing devices to be closer to the user for faster processing. However, as massive amounts of data are produced, the world may run out of storage. One answer for a future mode of storage is DNA. It offers a high storage density by encoding data into its base pairs [136].

Analysis, visualization, and interpretation of data allow conclusions to be made from large datasets that could positively impact the world around us. Reproducibility and transparency throughout the data lifecycle fosters trust between companies and consumers and a healthy research ecosystem.

5.5.2. Implications for NIST

NIST hosts public databases that encourage collaboration, drive innovation, and improve quality of life. NIST expertise in the integration, curation, and provisioning of critically evaluated data and models has allowed staff to become leaders within data initiatives. As data scientists are asked to extract meaning from larger and more varied datasets in a shifting technology ecosystem, being able to shift from one platform to another without retooling the computer environment is increasingly important. The NIST Big Data Public Working Group [137] created a Big Data Interoperability Framework and other products to help create software tools that can analyze large sets of data between computing platforms. The framework will most likely need to be updated for years to come in order to adapt to the ways data is collected, shared, and analyzed. Additionally, NIST engages with the FAIR data principles-driven Configurable Data Curation System (CDCS) platform for problem solving. This involvement led to activities including community standards, interoperability, and community development. NIST's expertise in cybersecurity is also much needed in the data storage space to prevent unauthorized data exploitation and protect user privacy. Finally, as machine learning and AI are increasingly used to analyze large sets of data, NIST can provide algorithm standards training to help eliminate bias and techniques for the smart use of limited data.

5.6. Drones and Autonomous Vehicles

5.6.1. Background

Drones have the potential to increase efficiency across a wide range of applications, from terrain mapping to agriculture. Perhaps their most beneficial use will be in dangerous and hazardous operations that reduce or eliminate human exposure to danger (e.g., disaster assessment). Future developments in drone technologies, including improvement in hardware, miniaturization, and advances in software, may enable surprising new uses for drones. AI will power the next generation and allow drones, and other vehicles, to make decisions and operate themselves "autonomously" on behalf of their human controllers. There are plans for such drones to hit the commercial market, including a new flying camera drone offered by Ring LLC. Others, like Sea Hunter, are currently used by the U.S. military.

Recent advances in AI, sensing, mechatronics, and related fields allow autonomous vehicles to operate in the same environments and situations that previously required direct human control [138]. However, some technologies like LiDAR (Light Detection and Ranging), have struggled to meet expectations, hampering wider adoption of drones and autonomous vehicles [139]. LiDAR a is less reliable technology under extreme weather conditions like heavy rain or snow. Also, its high cost prevents adoption by the consumer market [140]. Furthermore, there are still technological barriers to fully integrating the range of sensors and software needed for autonomous vehicles. Some of the software challenges include object detection, object analysis, human-like decision making, and fail-safe mechanisms that will allow cars to fail without putting passengers or other people in danger.

While drones and autonomous vehicles mainly exist in controlled environments for now, they will eventually evolve to include public spaces. Testing of autonomous transportation is currently underway and the Ring flying camera drones are set for release in 2021 [141]. Autonomous things will move from stand-alone to collaborative swarms, as illustrated during the 2018 Winter Olympics [142].

5.6.2. Implications for NIST

Prior to full commercialization, autonomous vehicles and drones will face technological, measurement, standardization, and regulatory hurdles. Many of the issues raised above will benefit from a measurement infrastructure that can provide assurance and confidence in autonomous systems. Areas where NIST may be asked to contribute include, but are not limited to: fundamental research in wireless co-existence and spectrum sharing; development of documentary standards that address interoperability, performance characteristics, and data security issues; improved sensors and actuators; evaluation of key performance metrics; and integration of sensor data.

The potential applications for drones, especially those in manned areas or non-segregated airspace, are not possible without the development and validation of certain key enabling technologies that include: detect and avoid"; "air traffic management"; and "command and control link". The development of these key enabling technologies is necessary for safe and autonomous drone application [143]. Finally, drones and autonomous vehicles will use sensors to automate controls and generate actionable alerts. Smart sensors and sensor networks will play a key role in enabling the full potential of these technologies [144].

5.7. Advanced Manufacturing

5.7.1. Background

The industrial and information revolutions have given way to a fourth industrial revolution known as the digital age. Advanced manufacturing in the digital age is signified by the following:

> (1) application of data analytics, autonomy, model-based engineering, and machine learning to manufacturing. Hardware advances that enable data collection and computing advances that allow data to be leveraged across the value stream, enhancing business value [140];

(2) computational modeling used for additive manufacturing. Integrated multiscale modeling methods that predict process–structure–property relationships, including the effect of defects. Computational materials research for additive manufacturing processes will enable efficient and accurate design, manufacture, and certification of a wide variety of 22nd century manufacturing systems [140];

(3) increased and evolved role for robots in manufacturing. More than two million industrial robots are in daily operation around the world, and the market for industrial robots continues to increase. As computer processing power increases and costs decrease, robots will operate more autonomously and provide increased flexibility. Robot applications will broaden in areas of logistics, defense, medicine, personal assistance, construction, cooperating robotic teams, and many others that require sophisticated operation [145];

(4) digital twin technology and its potential to boost efficiency, reduce costs, increase agility, and better manage maintenance schedules according to both past and projected operational needs. The digital twin concept involves simulating the future performance of a specific product or system based on current knowledge about the system and how it is operated [140]; and

(5) adoption of blockchain. In recent years, big tech companies like IBM and Microsoft as well as many startups have put significant effort into extending blockchain systems to various industries. Because the chain is tamper-resistant and the blocks are time stamped, a blockchain is a robust solution to authenticate data at any point during the product lifecycle. For manufacturing, it means that manufacturers can trust the data they receive from a designer [146].

5.7.2. Implications for NIST

Although advanced manufacturing has recently experienced considerable growth and publicity for its potential to transform the manufacturing sector, its promise is limited due to a lack of confidence in part quality. Improvements in material properties, consistency, and process control are necessary for companies and consumers to realize the potential of enhanced performance, reduced cost, and increased manufacturing speed. For example, the use of new advanced manufacturing methods to produce fracture-critical flight components requires extensive qualification efforts. Industry and regulators need a consistent framework, specific to the production and evaluation of advanced manufacturing processes. Standards need to be developed for materials, process control, personnel training, inspection, and acceptance requirements [140]. NIST is strongly positioned with its current programs to help address these needs.

Digital twin simulations have many potential applications, but also have significant technical, economic, and social limitations that inhibit widespread implementation. They include: the need to determine what information is needed for decision making (and how often); how to determine the proper level of fidelity for the simulations; and methods to validate probabilistic simulations. NIST provides important resources to the manufacturing community through engagement in standards development organizations and publishing the scope and requirements for a digital twin in manufacturing framework [147, 148].

Development of AI, machine-vision systems (MVS), and advanced sensor technologies enable the development of highly flexible industrial robots that become more sophisticated and, in some cases, more autonomous. Advanced MVS enable some industrial robots to recognize components or find faults. Advanced gripping devices and their enabling technologies could significantly increase the number of applications for industrial robots. There is, however, a need to develop standards for robots and interoperability components.

5.8. Human Augmentation

5.8.1. Background

The term "human augmentation" generally refers to technologies that enhance human productivity or capability, or add to the human body using natural or artificial methods. Aided by augmentation technology, humans will be stronger, faster, less prone to injury, and more productive. An increasingly wide range of technologies across different disciplines is enabling human augmentation, from bioengineering to robotics to mechatronics to AI. In the next five years, companies may begin to design tools that adopt human augmentation technologies. This can make the world more accessible to individuals with disabilities and in doing so, expand the workforce [149].

One frontier for augmentation is that of body-integrated sensors that would continuously monitor a person's state of health (e.g., nerves, muscles, and organs), creating a human intranet. Implanted sensors that constantly monitor the human state, (e.g., target analyte levels) and can provide feedback for treatment have huge promise [150]. By altering the corresponding genes to reverse or alleviate disease, the gene editing technique CRISPR has initial promise in clinical trials for genetic disorders including sickle-cell anemia [151] and blindness caused by a genetic disorder [152]. However, there are ethical considerations when employing CRISPR for human augmentation.

Human augmentations are being pursued to end physical disabilities through bionics and prosthetics with brain-computer interfaces. For example, powered exoskeleton technology has enabled paraplegics to walk again by reengaging muscles and the nervous system through repetitive motions. Additionally, as the population ages, exoskeletons that prevent knee and back strain can be used to address job shortages in sectors that require endurance, strength, and repetition. While it is expected that humans will eventually be replaced by robots in sectors like manufacturing [153], humans still performing manual labor and can benefit from being paired with robotic exoskeletons.

5.8.2. Implications for NIST

As human augmentation begins to permeate many aspects of life, the race to achieve leadership in this field could potentially lead to a competitive environment like the 20th century Space Race, which resulted in the rapid development of a wide range of new technologies. Some technologies associated with human augmentation include human genetic engineering, gene therapy, neural implants, brain–computer interfaces, nanomedicine, and 3D bioprinting. To accelerate the acceptance and use of these technologies, there must be standard test methods to evaluate their safety and performance. NIST contributions may come from its deep experience in industrial robotics, advanced materials, electronic engineering, battery systems, AI, bioscience, and cybersecurity. Better standards also foster competition by allowing manufacturers, including startups, to demonstrate the performance of their products using agreed-upon metrics. NIST can act as a neutral party, providing technical guidance and leadership in standards development while helping industry safely extend human performance. A critical aspect of adoption of these technologies is human factors, and NIST expertise in human factors research can help identify issues in using these technologies. NIST is already contributing through gene editing and exoskeleton/suit standards, and by automating development of biological sensors with an eye to clinical applications.

5.9. 5G and Next Generation Communication

5.9.1. Background

Despite the promise of 5G networking technology (dramatically faster connectivity for smart machines, autonomous driving, and media consumption), the U.S. lags behind China, South Korea, and the UK in 5G deployment. This may change as telecommunication companies in the U.S. promise more comprehensive rollouts of the technology they piloted in late 2018 [139]. Key features of 5G include high throughput, low latency, high mobility, and high connection density. The widespread use of 5G technologies is expected to produce $3.5 trillion in output and 22 million jobs globally by 2035 [154].

Developments in 5G networking include the rapid creation of software-defined services, support for a greatly expanded IoT, the proliferation of cashierless stores, the use of AI to enhance communications, and the use of cellular radios for police and other emergency services [155]. 5G can enable edge computing because it supports enhanced connectivity, enhances computing power, and allows for better performance of devices at lower energies [156]. However, technical impediments remain. Use cases for 5G will bring new requirements for storage, computation, and network domains, and will introduce new risk to the confidentiality, integrity, and availability of enterprise and user data.

5.9.2. Implications for NIST

For the design, evaluation, and deployment of future 5G networks, it is essential to have a 5G channel model that is well-supported by diverse measurements across different frequency bands, deployment scenarios, and geographical areas. The 5G mmWave Channel Model Alliance led by NIST provides a venue to promote fundamental research into measurement, analysis, identification of physical parameters, and statistical representations of millimeter-wave propagation channels. In establishing the alliance, NIST brought together more than 130 participants to solve the most pressing modeling and measurement challenges facing the deployment of 5G wireless communications. The output of the alliance will be incorporated into new standards, specifications, and best practices benefitting the entire industry. As a national leader in cybersecurity, NIST will be asked to take a lead role in helping to secure this massive IoT ecosystem.

NIST is highly involved in 5G-related efforts and has identified a number of measurement challenges related to 5G technologies. Because these networks will rely on high-density deployments of devices, one challenge area is interference of wireless signals. 5G will utilize higher frequency spectrum bands, which have different (and less studied) propagation properties from lower frequency bands on which current networks operate. New antenna systems will need to be built and calibrated to accommodate 5G networks, and there is still work to be done in using telemetry and measurements for autonomous control of communications systems [156].

5.10. Space

5.10.1. Background

Not since the Space Race of the 1960s has there been so much activity in the aerospace ecosystem. The coming years hold great potential to reach new heights and bolster the American space ecosystem. In 2020 alone, there exists the promise of the first space tourists, the deployment of hundreds of global internet satellites, the flight of National Aeronautics and Space Administration (NASA) astronauts from American soil for the first time since 2011, and progress towards humans landing on the moon once again (a 2024 goal of the Trump administration). Additionally, NASA celebrated the 20th anniversary of continuous astronaut residence in the International Space Station (ISS). Yet, the way the space economy functions is vastly different than pre-2009. Over the past decade, the space economy has gone from an enterprise of $175 billion to one of almost $415 billion and is expected to be worth around a trillion dollars in two decades [157]. Hundreds of private companies have invested in the space exploration enterprise, with $18 billion of investment from 2009 to 2018 and $3.25 billion in 2018 alone [158, 159]. Companies like SpaceX saw an opportunity when the U.S. ramped down the space program in the 2000s and have driven innovation in space flight over the last decade [160]. As the commercial market becomes more crowded, the 2020s promise results after a decade of development.

Space is getting crowded. There are over 20,000 artificial objects orbiting Earth including 1500 satellites [161]. With an increased number of stakeholders in the space biosphere, including significant international players like China, Russia, and India, the amount of space debris in low Earth orbit is also growing due to human-generated objects, including parts of rockets and non-functioning satellites, or accidental explosions or collisions of high-speed objects [162]. Global space traffic monitoring is necessary, but there are currently few internationally accepted rules or standards regarding how to move about. A system like air traffic control for commercial airlines needs to be developed, but the small size of a large proportion of debris makes this challenging. The United States Space Force (USSF) was recently established as a new branch of the Armed Forces. Its mission is to "protect U.S. and allied interests in space and to provide space capabilities to the joint force" [163]. Time will tell how the militarization of space will impact the space ecosystem. International cooperation is necessary as we continue to explore and expand into the universe.

To accomplish the lofty goal of getting humans to Mars, rockets and spaceships must go further and faster. Crews must be able to repair anything that goes wrong during a mission, which may require parts produced by 3D printers. Additive manufacturing aerospace technologies could also enhance production of materials used on Earth in unique conditions [164]. Materials for spaceships and satellites are not the only parts needed. Being able to grow food in space could reduce cargo loads and costs required to feed astronauts; it currently costs $2,000 to ship a lemon to the ISS. Synthetic biology offers promising technologies through cellular agriculture where meats like beef and poultry can be grown in a lab. Textiles from microbial production would allow astronauts to recycle old materials and grow new ones [165].

5.10.2. Implications for NIST

With an increased number of satellites and space missions, advanced manufacturing for materials production and research for development of new aerospace materials will help drive innovation forward, while making these launches more efficient and decreasing the amount of waste left behind in the process. NIST is currently contributing to research and development of aerospace materials through several public-private partnerships from a center of excellence and regional manufacturing networks including Manufacturing USA [166] and the Hollings Manufacturing Extension Partnership (MEP) [167]. The NIST Advanced Materials Center of Excellence, Center for Hierarchical Materials Design (CHiMaD), has undertaken research projects that support materials developments related to SpaceX projects. Though these projects are currently less active, the SpaceX and Tesla Vice President for Materials Engineering remains on the Center's advisory board. As a more safe and sustainable space environment emerges, standards analysis and advancement for space safety are needed. NIST's unique expertise in cybersecurity can aid this effort [168]. Another way NIST is uniquely poised to aid in the aerospace ecosystem is through the development of standards and sensors for space measurements. Sensors in satellites are calibrated by NIST light standards to ensure that measurements taken are accurate and can be compared to observations from other sources [169]. As more satellite constellations are placed in the lower orbit, standards will need to be updated to ensure accurate measurements.

NIST is engaged with the DOC's Office of Space Commerce to support the needs of a commercial space sector. In September of 2019, NIST (Boulder) hosted a joint workshop on Space Commerce with the Office of Space Commerce, NOAA, NTIA, and the University of Colorado Boulder. The resulting NIST Space Commerce Workshop Report [168] identifies a number of priority research needs and other issues that need attention to support space commerce.

5.11. Grand Challenges for Laboratory Focus Areas

Beyond the noted technology drivers, cross-cutting technology capabilities will likely shape the future. The laboratory focus areas encompass four themes that are especially relevant to NIST: Quantum Information Science (QIS), AI, Engineering Biology, and IoT. These areas hold the promise of transforming U.S. manufacturing, communications, health care, transportation, and beyond. They will also radically alter how NIST approaches its mission delivery, both by unleashing new measurement capabilities, and by requiring NIST to develop new methods for measurement dissemination that best serves the needs of new and evolving industrial sectors.

For instance, AI and QIS are two disruptive technologies expected to influence, enhance, or otherwise provide a springboard for innovation across multiple technology disciplines. International governments are currently investing billions of dollars in infrastructure projects, workforce training, and research to "win" the AI and quantum supremacy race. Similarly, technologies that drive IoT are ready to support system implementations in new, large-scale application environments. IoT connects systems and devices to people in ways that will drastically change the landscape of many sectors (e.g., autonomous cars in transportation, automated supply chains in manufacturing, and connected first responders in public safety). Engineering biology, which underpins the bioeconomy, offers innovative solutions across global healthcare, agriculture, manufacturing, and environmental challenges.

The purpose of a focus area is to clearly articulate to internal and external stakeholders what is being accomplished in support of the NIST mission. The focus areas are intended to be forward-looking, impactful, and an expression of shared goals held by NIST leadership and staff. They require an increased concentration of resources and represent a commitment by NIST leadership to achieve clearly defined goals. In 2019, the Associate Director for Laboratory Programs directed the NIST Laboratory Directors to identify a grand challenge for each focus area:

5.11.1. Quantum Network Grand Challenge (QNGC)

Within the Quantum Science program, NIST has three main thrusts: 1) Foundational quantum science and metrology, 2) Applied research to engineer and improve the robustness of prototypes: Quantum Engineering, and 3) Realization and dissemination of the units of measure: The Quantum SI. Under Quantum SI, investments are made to develop improved laboratory realizations as well as NIST on a Chip based SI-traceable calibration devices.

> Vision: NIST will advance the metrology of quantum entanglement and superposition to provide a foundation for the encoding, transmission and use of quantum information.

A specific grand challenge for QIS is the construction of a prototype quantum network, a key element in the long-term evolution of quantum technologies. The quantum network would serve as the skeleton for secure and highly efficient quantum information transmission linking together multiple quantum devices and sensors. The crucial aspect of a quantum network is the ability to distribute quantum entanglement as a usable resource. This fundamental research provides foundation for robust standards to retain U.S. leadership in the QIS ecosystem. NIST will leverage existing strengths in qubits, QIS, optical communications, and quantum transducers to develop the necessary measurement infrastructure, including quantum network testbeds and key enabling technologies. Through this effort, NIST will enable U.S. industrial development of quantum communications for quantum-enhanced sensing, distributed quantum computing, and improved secure communications. By focusing on a goal of developing quantum network testbeds, NIST can address new measurement challenges, understand performance metrics, and start the development of protocols and documentary standards needed for this future technology. This, in turn, will help advance U.S. industrial development of quantum-information technology.

As the country's NMI, NIST must continue to develop and expand technical competence in areas underlying quantum technologies to provide industry with measurements and standards in this rapidly evolving field. To develop competence in the near-term, NIST will develop one or more prototype quantum network testbeds that can enable characterization/calibration of components that are connected to the network, as well as characterization of properties of the network itself, and the development of standards and best practices.

5.11.2. Internet of Things (IoT) Grand Challenge

The full benefits of IoT will be achieved when IoT users have confidence that their systems are trustworthy. The figures of merit for trustworthy IoT systems include *reliability*, *resilience*, *security*, *privacy*, and *safety*. NIST will focus on the core mission of state-of-art measurement solutions and robust implementation practices to expedite large-scale adoption of interoperable, trustworthy IoT solutions. To accomplish this, NIST will position itself around three key strategies based upon:

> Vision: Assuring the trustworthiness of IoT systems by developing quantitative metrics, standards, and guidelines for critical applications.

1) measurements, research, and standards to support reliability and resilience of IoT systems;
2) guidelines for assessing IoT security, privacy, and safety; and
3) strategic collaborations and partnerships to accelerate early adoption and prioritize areas of greatest need.

NIST will use a two-pronged approach to address the critical factors that comprise trustworthiness. First, NIST will develop guidelines and standards to address security, privacy, and safety issues related to IoT systems. Second, NIST will create a deployable, metric-based Industrial IoT (IIoT) testbed uniting NIST expertise in wireless communications, manufacturing, and AI. The outcomes of this ambitious program will enable wireless device manufacturers, integrators, and end users to make investment decisions based on a rigorous metrological foundation. Success will require a multidisciplinary effort with expertise in computer science, electrical engineering, mechanical engineering, and physics.

Together, these guides and testbed will enable IoT designers to develop new technology and give consumers the confidence necessary for adopting these technologies for use in mission critical industrial applications such as advanced manufacturing, public safety, and healthcare. This body of work will provide NIST with a unique footing within the international NMI community by uniting research programs on security and privacy with NIST-rigorous measurement techniques for 5G and IoT applications.

5.11.3. Artificial Intelligence Grand Challenge

To support the responsible development, deployment, and use of AI for maximal benefit, there is a need to set out the main requirements for trustworthy AI, and appropriate methods, standards and solutions to implement those requirements when developing, deploying, and using AI, as well as to establish metrics and benchmarks for AI hardware.

There have been incredible advancements in AI research in past years, but also several important illustrations of the harm these systems can cause when designed poorly or deployed without sufficient understanding or appropriate oversight [170]. The lack of understanding of, ability to communicate about, and trust in AI systems will slow the adoption of AI or lead to the inefficient uses of its systems. Additionally, because AI progress is tied to hardware advancements, new technologies (beyond graphic processing units) need to be developed that push the physics of AI to deliver radical improvement over the next decade, with innovation and co-development from algorithms, to systems, and to devices.

> Vision: NIST will become an authoritative source of measurement tools, capabilities, and data necessary to define, develop, and evaluate trustworthy AI.

NIST is ideally the best fit to address these concerns, as it is located at the intersection of foundational and applied research. NIST has a proven track record of working with industry to develop valuable materials to build trust in technology and help advance the U.S. economy. One of the goals of the Grand Challenge is to develop the *Metrologists' Guide to Trustworthy AI*, a source of information and solutions that will provide the research community, developers, users, organizational leaders, businesses, and process managers the language to communicate AI at all levels. This guide includes innovation to application, strategic to tactical, as well as the tools and solutions to understand, measure, and manage the development, deployment, and operation of AI systems, including identifying informative references and international standards. While this is one component of the broader AI program, NIST will also perform research and develop measurement tools that the community can use for developing and deploying trustworthy AI.

5.11.4. Engineering Biology Grand Challenge: Living Measurement Systems Foundry

NIST has taken on a challenge to demonstrate the first predictive engineering of a genetic sensor that provides quantitative measurements of its local environment. It will be done through a platform that is both scalable and generalizable, across a range of microorganisms used in industry.

Genetic sensors, consisting of interacting proteins and nucleic acids that are encoded in DNA and produced as part of a living cell, give cells the ability to measure input signals such as temperature, molecular concentrations, or light. They transduce those signals into biomolecular output (i.e., gene expression) inside the cell. The ability to create new genetic sensors with made-to-order characteristics would allow engineers to create novel organisms with advanced functionality to sense and respond to dynamic and unpredictable environments. Being able to produce these sensors (biological measurement systems) is the key to advancing synthetic biology from an extension of metabolic engineering used to manufacture chemicals in fermenters, to a new manufacturing

> Vision: Enabling the safe, predictable design and control of biological systems to manufacture innovative new products such as advanced therapeutics, chemical feedstocks, and advanced materials.

paradigm. This shift will require orders of magnitude improvements in the number of variants to screen and the number of expressed proteins (the signal).

To meet this challenge, NIST will:

- build the NIST Living Measurement Systems Foundry, an automated high-throughput measurement platform to perform controlled Darwinian evolution screening and testing to predictively engineer genetic sensors using competition in a fluctuating environment; and
- develop ML algorithms to optimize the evolutionary process by controlling the targeting and rate of mutations without protein structure information.

For this effort, significant improvements to NIST data infrastructure is needed. Specifically, the need to rapidly move data, store data, and analyze data via leading edge ML/AI computing resources. NIST must continue to leverage its existing inhouse capabilities with those of other partners through collaborative efforts like JIMB (Joint Institute for Metrology in Biology), IBBR (Institute for Bioscience and Biotechnology Research), and NIIMBL (National Institute for Innovation in Manufacturing Biopharmaceuticals). The DOD has reached out to NIST for support in developing the newest Manufacturing USA Institute on synthetic biology and engineering biology.

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