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In the Realm of the BARELY FEASIBLE

Complex challenges facing the nation require a new approach to ramping up innovation: solutions R&D.

What would the Vannevar Bush of 1945 make of 2020? He could beam with justifiable pride in having paved the way for an information revolution, an eightfold growth in real gross domestic product, diseases cured, and a Cold War ended. Seeing the current pandemic, he would be perplexed that the nation's response looks devastatingly like the one he would have experienced in 1918. Seeing protests, he might grieve to learn that Black intergenerational mobility is as poor as it was when he was born in 1890. He would be astonished to see the scale of disinformation campaigns manipulating our worst instincts to sow division. And he would be confounded by the nation's weak response to the massive problem of climate change.

Just as World War II was ending, Vannevar Bush wrote *Science, the Endless Frontier*, and it remains the touchstone for federal support of research and the frame we use to explain its social value. Starting with national purposes and national needs, he wrote of the goal of improving health and longevity. He wrote about maintaining military preparedness even in peacetime. And most poignantly, after the Depression and years of combat, with millions of GIs about to come home, he wrote, "One of our hopes is that after the war there will be full employment, and that the production of goods and services will serve to raise our standard of living." Then Bush identified a gap in American innovation that called for a new way of working to help achieve these ambitions: robust basic research, conducted at universities, and supported by the federal government.

It was a time when the nation's GDP was over half of the world's total production, as much of the rest of the world was buried under the rubble of war. It was a time when manufacturing and agriculture were the backbone of our economy. It was a time before the first artificial satellite, before the transistor, before we knew that DNA is a double helix.

The challenges of a new era

I reread *Endless Frontier* in 2017 as I was concluding my term as director of the Defense Advanced Research Projects Agency, or DARPA. It brought home the fact that the contributions I'd gotten to make over 30 years in public agencies and private companies were all in the context of an exceptional American innovation system that grew in the wake of that document. But I couldn't stop thinking about the ways in which our country's challenges differed from those that Bush described in July 1945. His trio of economic growth, health, and national security will always be essential challenges for the United States, but today they must be understood and addressed in new ways. Economic growth has brought with it a damaging growth in inequality and further entrenched racial inequity. We have focused intently on biomedicine but not on preventing illness and maintaining good health across our whole population, again reinforcing unacceptable inequities. Major security threats change at a much faster pace and go beyond the need to deliver firepower on target, now encompassing threats of cyber attacks, biological weapons, and disinformation. And we face new challenges unknown in Bush's time. Climate change's devastations have only started, and the job ahead to mitigate greenhouse gas emissions is immense. The Information Age has brought with its marvels an array of inadvertent and dangerous consequences, including privacy erosion and threats to our democracy.

Inspired by *Endless Frontier*, a broad set of organizations, incentives, and relationships evolved after World War II. To meet the challenges we now face, we need a generational advance in our innovation ecosystem with new methods, new participants, and new incentives.

DARPA gave me one of the world's great perches for scanning the research horizon, and, with *Endless Frontier* in

mind, I was mulling over what new ideas might be brought to the challenges ahead. That was the start of a journey that led to founding Actuate in 2019 with fellow DARPA alumnus Wade Shen. Actuate is a new nonprofit organization to conduct what we call "solutions R&D" programs. We want to accelerate the development of new forms of innovation by prototyping them. Our work will be to design and run programs that do two things: demonstrate specific new breakthrough solutions for society's hard problems, and demonstrate what an effective innovation model can look like in these areas. And by hard problems, I mean hard. Our four focus areas are: data and information we can trust, robust population health, opportunity for every person, and mitigating climate change.

It takes an ecosystem

The story line of the transformations resulting from *Science, the Endless Frontier* is generally about curiosity-driven basic research leading to insights that are then commercialized.

Curiosity is indeed one part of the story. Here's an example. Every time the blue GPS dot blinks on the map on my phone, I think about a couple of young researchers at the Johns Hopkins University Applied Physics Laboratory. During the excitement and panic of Sputnik, these two lugged their radio gear up to a rooftop where they listened to the Doppler shift from that first satellite that humans had ever flung into orbit. The basic insight about a new means for geolocation grew from that seminal moment.

But our two heroes are only part of the GPS story. Ideas form in a context, and in 1957 that context was a mix of geopolitics, institutional arrangements, and technologies. The prior decade's world war had cemented a new relationship between academia and the national security enterprise, including Defense Department support for the Applied Physics Lab. Communications, precision timekeeping, and radio frequency engineering were racing forward, and satellite technology joined the list of burgeoning fields at that very moment. The collision of these technologies was opening a multitude of new opportunities in that period, and revealing many new phenomena to be curious about. The Cold War added a sense of existential urgency that encouraged bold experimentation.

And that's just the start. Taking GPS from a kernel of insight to ubiquity took billions of dollars and decades of investment by the Defense Department to engineer and then deploy an extraordinarily sophisticated system of satellites packed with precision technologies. It took the application of the theory of general relativity to correct for the shift in timekeeping by atomic clocks on a distant orbit. It took two presidential orders that opened GPS signals to public use. And it took companies and entrepreneurs and investors to put GPS receivers into ships, planes, trucks, tractors, cars, computers, and eventually phones. It takes nothing away from those two radio researchers, or from Einstein for that matter, to understand and acknowledge that all of this was needed for those little blue dots to appear on our maps.

Advanced materials, new energy technologies, medical therapies, integrated circuits, the internet, wireless and mobile technologies, data science and artificial intelligence—each new technology has its own unique story of how it germinated, grew, blossomed, and spread. But the technologies that surround us share this characteristic: every one of them was the result of our complex, convoluted, robust research and development ecosystem. Each one required basic research, playing out among emerging fields of inquiry; product development and commercialization; and policies and public support to encourage its development, initiate its adoption, and navigate its unwanted consequences. Each required an interplay among researchers, producers, investors, policy-makers, and customers; each reflects the interplay of R&D with markets and societal needs.

Yet we lack a systematic understanding of how to nurture the sort of rich ecosystem we need to confront the societal challenges facing us now. Over 75 years, the federal government has dramatically increased its support of research, and universities and national labs have built layers of incentives and deep culture for their research role. Companies have honed their ability to develop products and markets, shifting away from doing their own fundamental research in established industries. American venture capital and entrepreneurship have supercharged the start-up pathway for commercialization in some sectors. But we haven't yet put enough energy into understanding the bigger space where policy, finance, and the market meet to scale component ideas into the kind of deep and wide innovations that can solve big, previously intractable problems in society.

These sorts of problems aren't aligned to tangible market opportunities or to the missions of established government R&D organizations today. The philanthropic sector can play a pivotal role by taking the early risk of trying new methods for R&D and developing initial examples that governments and markets can then adopt and ramp up.

The hypothesis behind Actuate is that solutions R&D can be the starting place for catalyzing this necessary change in the nation's innovation ecosystem. Solutions R&D weaves the threads of research from multiple domains together with lessons from the reality of use and practice, to demonstrate prototypes, develop tools, and build convincing evidence. Because it reaches into and connects all the parts of the innovation system, solutions R&D is a powerful way to ratchet the whole system up faster, once some initial elements of research and implementation are in place. Doing it well takes a management approach that combines a relentless focus on a bold goal with the ability to manage the high risk involved in creative experimentation.

Doing it well also changes minds about what's possible.

DARPA, empowered

The Defense Advanced Research Projects Agency has been doing solutions R&D well for six decades. Its $3.5 billion annual budget is a small slice of federal R&D, but it has a tremendous track record of generating breakthroughs for defense and for the wider world. My colleagues in the Defense Department understood DARPA as the originator of stealth aircraft, precision strike, and long-duration unmanned aerial vehicles. In the Silicon Valley part of my life, I found the tech community saw DARPA as the place that seeded multiple waves of artificial intelligence, a host of advanced semiconductor technologies, and—of course—the ARPAnet and the internet. DARPA programs across these areas drew on basic research supported by other agencies such as the National Science Foundation, which pumped more funding in as that research's potential was revealed. And as DARPA's programs showed what was possible, they catalyzed massive other investments, public and private, that led to the systems, products, industries, policies, and practices that ultimately changed how our military fights and how people around the world live and work. This is how solutions R&D can stimulate the much wider innovation system—so that it ultimately changes the future.

During my time leading DARPA, this track record was our benchmark for impact as we built a portfolio of hundreds of programs that drew from fields as diverse as space science and anthropology, cyber-physical systems engineering and synthetic biology, electromagnetics and advanced math. Time will tell if that work meets our high aspirations. Early signs are promising. The Port Authority of New York and New Jersey now monitors radiological and nuclear threats continuously and robustly across a wide region by using our system of networked sensors. The military services are starting to shift to the flexible new architectures we designed to outpace adversaries and upturn our own sclerotic process built around monolithic defense systems. Start-ups are commercializing automated tools and processors developed in our programs to bring the revelations of machine learning to whole new classes of problems. And the first new vaccines and monoclonal antibodies to enter clinical trials for COVID-19 came from our programs that aimed to shrink the time to solutions from years to months.

DARPA's historic track record has also made it a model of government-sponsored innovation. Behind every call for "an ARPA for X" (where, in recent years, X = energy, intelligence, health, agriculture, Japan, Europe, or Britain) is a yearning for R&D that throws open new doors to solutions. Not every attempt succeeds. But ARPA-E for energy and IARPA for intelligence are now underway, and they are fulfilling the promise of delivering fresh and important advances by applying the key elements of the DARPA model in other fields.

Inspired by the experiences and lessons of DARPA, Actuate is adapting that approach to a different set of societal challenges. This isn't a copy-and-paste exercise. We're going to the heart of the DARPA model to figure out how that can be brought to life in very different contexts. As with any complex, dynamic system,

VISIONS OF THE SPACE FRONTIER

Posters from China, the Soviet Union, and the United States.

Chinese citizens cheer for a Soviet rocket in a poster from 1957, reflecting the friendly relationship that would come to an end only a few years later. A Prometheus-like figure reaches for the cosmos in a Soviet poster with one hand while holding a hammer and a sickle in the other. Charles Shultz's beloved icon Snoopy—the official NASA spaceflight safety mascot—appears in American posters, adding an element of familiarity, reassurance, and cuteness in an effort to appeal to young people and the broader public. These are just a sampling of the space imagery used by China, the Soviet Union, and the United States during the mid-twentieth century.

Space iconography was a persuasive communications tool throughout the space race. Posters played an important role, especially at a time before ubiquitous home televisions, personal computers, and smartphones. The posters' purpose was to persuade, inform, and instill national pride for each space program without giving away any closely guarded technological secrets. Posters efficiently and effectively delivered their messages, using symbols understood by millions. Graphically bold, aesthetically pleasing, and whimsical, they reflect the styles and ideologies of their cultures and era.

Cheers for the Soviet Union's rocket that went to the sky, 1957, designed by De Yugong, Collection International Institute of Social History (Amsterdam). This poster is from the years when the Soviet Union had a technology and scientific training transfer program with China. It came to an end in the early 1960s.

the whole is greater than its elements. Many elements have been extensively studied, and one consistent observation in particular matches my experiences in the agency. The core of the DARPA model is a "head in the stars, feet on the ground" program manager, empowered to design and run a focused program with the potential for high impact.

Empowered program managers start by understanding the systems context in their area and looking for leverage points—places where a new approach could lead to a broader change. They define a bold goal. It must be in the realm of the feasible, but perhaps only barely so. Indeed, "barely in the realm of the feasible" is what keeps others from trying it. They design the program to rigorously wring out risks. They then run the program by tapping exceptional talents in all kinds of companies, universities, and other organizations.

A successful program ends with three results: a convincing demonstration of the program's breakthrough goal; a community of researchers and technologists who are imbued with the program's vision, have shown it to be possible, and are able to move it forward; and decision-makers ready to fund and implement the results with product development or other action so that it can ultimately achieve full scale and impact.

Over time, with resources and room to run, a solutions R&D organization can create a culture in which every participant runs to work in the morning to change what's possible—and then does exactly that.

The empowered expert program manager approach for solutions R&D traces back to before World War II, when the Rockefeller Foundation developed it to create the advances that would become the Green Revolution. During the war, that management model was imported by the Office of Scientific Research and Development, headed by none other than Vannevar Bush, to manage programs developing radar, the proximity fuze, and the atomic bomb. After the war, the empowered management model was adopted by the Office of Naval Research, and then by DARPA when it started in 1958. With Actuate, we seek to bring this model back to the realm of philanthropy to start building the capacity to tackle very different kinds of societal needs—enabling government and the market to adopt it and scale it up.

The revolution in three parts

Why do we believe that a solutions R&D approach can be applied to our vexing societal challenges today? Progress often comes from the confluence of hard problems and new ideas that can lead to solutions. Revolutions in the physical sciences, in biology, in engineering, and in math and computer science gave birth to the breakthroughs that changed the face of our economy, our security, and our health in the last century in ways previously unimaginable. That story is far from done.

Today, a revolution is just starting to emerge as information technology pervades every field of inquiry and action. It's changing our thinking about complex systems, and it's especially powerful across the social, behavioral, and economic sciences. This new revolution has three parts.

The first is well known: abundant data and the tools to understand it. We now have voluminous data about people and organizations—sometimes noisy and messy, but phenomenally valuable in its sheer quantity and freshness. We also have deeper and richer data than ever before about physical and natural systems: chemical processes, electric grids, crops, oceans. In parallel, data science and artificial intelligence tools let us analyze these masses of data and extract patterns for a seemingly endless

fountain of correlations.

The second is perhaps less visible: the ability to model complex systems and to reason about underlying causes. Such models capture the interactions and feedback loops that characterize every interesting problem, Such models capture the interactions and feedback loops that characterize every interesting problem, allowing us to further deepen our understanding of the conditions under which certain outcomes occur. This is how

Roaming outer space in an air ship, 1962, designed by Zhang Ruiheng, Collection International Institute of Social History (Amsterdam).

scientific understanding grows—and it's also how we explore the path from evidence under one set of circumstances to broadly applicable solutions.

The third applies to problems that directly involve a wide population of individuals: the ability to reach billions of people in individualized, personalized, interactive ways through devices carried in their pockets.

Voluminous data, reasoning about complex systems, personalized interactions at scale. These are exciting new capabilities that let us experiment, learn, iterate, and improve our capacity to intervene in addressing complex societal problems in ways we could barely have imagined in the past. This capacity does not offer an instant solution to all the problems of the world. But it can shift the boundaries so that some of our intractable problems become tractable.

New hope for hard problems

At Actuate, the four challenges we have chosen to pursue are critical to the future success of our society. Each is the sum of many component problems that may seem beyond reach today. Yet new ideas, methods, and tools now make it possible to form and test fresh hypotheses with the potential to crack open new solutions.

Data and information we can trust. The information revolution germinated from utopian dreams of empowerment and connectivity. But today, even as we reap its wonderful benefits, serious problems of privacy and trust are undermining democracies and limiting the full potential still to be gained from the information transformation.

One great paradox of the information age is that personal information is the most valuable data for addressing societal problems and simultaneously the most dangerous data for individual privacy. Within banks of data are insights about how to better educate our children, avoid the diseases that loom ahead for millions, reduce crime and incarceration, improve public services, and much more—but also how to facilitate political persecution, insurance discrimination, identity theft, and much more. Protecting privacy protects democracy and individual freedoms, but it prevents the use of data that can help solve societal challenges.

Because abundant data is a cornerstone of the next generation of solutions R&D, solving the data-privacy problem is itself a foundational solutions R&D problem. That's why it's one of the first programs that Actuate is developing.

An array of new technologies is just starting to make it feasible to ease the tension between data and privacy. Using data for computation while it's still safely encrypted is now possible. The field of differential privacy has developed methods to track privacy leakage. New techniques can allow researchers to clean and link multiple datasets without having to see the raw data. These emerging approaches require highly specialized technical expertise today, and we can't yet combine them to yield privacy-preserving computations at a practical cost and speed across a wide range of uses.

Actuate is developing a program called DataSafes to research and demonstrate a data sharing system that allows multiple data owners to maintain privacy guarantees during the entire cycle of statistical analysis, from data cleaning and linkage, to model discovery, to generating results from those models.

If successful, this new framework would make personal data analyzable and private at the same time. It would allow individuals, companies, and agencies to provide access to more and more valuable data with confidence that it will

remain private while helping to solve major challenges.

Robust population health. The United States outstrips every other nation on per capita health spending, and yet dozens of other countries have lower infant mortality rates and longer life expectancy. Although the nation spends $3.5 trillion annually on health, less than 3% of these funds support public health, which focuses on prevention and the overall health of our population. Our weakened public health systems are scrambling to try to contain infections and deaths during the current pandemic, leading to a stunted economy that's thrown tens of millions out of work. Other countries show that this doesn't have to be the case.

We will need a vigorous renewal of population health—distinct from biomedicine—if we are to overturn this dismal situation. Here's one specific example of a role that solutions R&D can play. We've had solid proof for nearly 20 years that coaching for healthy habits is the most effective way to prevent the onset of diabetes for those at risk. Yet coaching is expensive, insurance coverage is limited, and doctors rarely prescribe it. A bit of progress has been made, but the problem remains: fewer than of one percent of Americans at risk of diabetes are in an evidence-based coaching program. Over 30 million Americans afflicted with diabetes, another 88 million at risk, higher rates for Black and Hispanic populations, millions of cases of cardiovascular disease and cancers also preventable with healthy habits: such numbers tell us the true scale of this missed opportunity in illness, death, inequity, and financial costs.

Today, behavioral research, data, and machine learning could be combined to create a radically better personalized coaching system. It would start with a secure data system on a smartphone that puts control directly in each person's hands. It would provide them with a realistic assessment of day-to-day activities and eating patterns from smartphone sensors and linguistic analyses of texts. It would provide on-the-spot incentives to make good choices, offering the potential to be even more effective than previous coaching approaches. And it could do so at a fraction of the cost of coaching by trained specialists.

The work ahead is risky—now just barely feasible. But if an R&D program can develop and prove this kind of solution in trials with many different people at risk of diabetes, it can help change the course of our chronic disease crisis.

Opportunity for every person. Financial mobility has stalled for many people and inequality has grown to a breaking point. College graduates have tripled their wealth over the past four decades, but the assets of those without college degrees have stagnated. Racial inequity is a longstanding, embedded factor. A recent study of intergenerational mobility across 12 decades found that "the headwinds black men have faced are race-specific in the sense that whites from similarly disadvantaged backgrounds experienced greater upward mobility and higher average income in every cohort since 1880."

An intergenerational lack of mobility is fundamentally inconsistent with the promise of America. And everyone loses out when only a relative few are able to live to their full potential and make their wholehearted contribution to our society's future.

Solutions R&D can help. Last year's Nobel Prize in Economics went to Abhijit Banerjee, Esther Duflo, and Michael Kremer "for their experimental approach to alleviating global poverty." They developed the practices of randomized controlled trials to learn what does and doesn't work in education, health, and poverty alleviation, touching many millions of lives and changing development economics in the process.

Research efforts such as these are a hint of what's to come. Social science is at an inflection point, for the first time capable of seeing in detail the multitude of factors, influences, and policies that interact to either improve or damage an individual's opportunity in society. Data analyses such as the Opportunity Atlas created by Raj Chetty and colleagues reveal the fabric of inequality in astonishing and valuable ways. For example, this work shows that in virtually every zip code nationwide, even from well-to-do neighboring households with similar incomes, Black boys grow up to make less than white boys. From such analysis can come new hypotheses, new experiments with new ways to assess progress and outcomes, and new learning. Social science is ready to contribute to solutions in powerful new ways.

Here we have the social and natural sciences converging with the information revolution, exhibiting all the signs of the birth of a new set of powerful technologies.

Mitigating climate change. To avoid the most calamitous consequences of a changing climate, we will need to eliminate or offset essentially all greenhouse gas emissions by 2050. This seems at first glance to be a fairly traditional challenge for R&D and innovation. Over the past decade or so, wind and solar electricity have scaled faster than most people predicted; they're currently mitigating about 5% of the world's greenhouse gas emissions and continuing to grow rapidly. But here's the problem: getting to this point took many decades from the first lab results, the first products, and the first companies. This is a sobering reminder that we don't yet know how to implement deep infrastructural change on a massive scale in a very few decades. Meeting this challenge will require new kinds of innovation.

Because greenhouse gas emissions come from virtually every kind of human activity and enterprise, we will need to scale up hundreds of different new technology solutions, in virtually every corner of the economy. Here, the stumbling blocks involve the details of manufacturing and supply chains, the new skills needed and the old jobs lost, finding sites for new installations, and the high cost of capital for a first-of-its-kind system. The mechanisms

of the market play a big role in these areas, but the market moves only at the pace at which profits and returns can be generated. As with many earlier infrastructures that were essential to the future functioning of our society (railroads and electricity, for example), the public sector plays an essential role here too.

Solutions R&D can also help us deal with this complex systems challenge. We can learn from ongoing activities, understanding how to speed and expand them with the tools of applied economics, behavioral science, and policy research. What aspects of testbeds and demonstrations most help to reduce risks and ease the transition to real-world operations? If a state government accelerates local deployment of a new climate solution, can their methods work for the needs of a different region? What allows a market exchange to expand and function at large scales, and can those lessons be applied to an exchange for carbon credits? These kinds of questions can shape new hypotheses, experiments, and real-world learning that accelerate the scale-up process for decarbonization across the entire economy.

Across Actuate's programs, we aim to do two things: show what specific fresh solutions can do, and show how solutions R&D can work. If we're successful, our efforts can accelerate a generational advance across our innovation ecosystem—not just fuller solutions R&D but also the robust basic research and implementation to address different classes of problems. This is how we ratchet up the twenty-first century innovation ecosystem we need to address the deepest challenges facing the nation.

Ethics from the start

These are exciting times. Here we have the social and natural sciences converging with the information revolution, exhibiting all the signs of the birth of a new set of powerful technologies. And that makes this a good point to ask: what could possibly go wrong? It's an essential question whenever we're working on powerful technologies—of any kind.

Look back again at GPS. Along with all its wonderful commercial applications have come new questions about privacy and who has the right to use your GPS data. In the Defense Department, GPS was a key enabler of the biggest strategic shift in military technology in the past half century: from mass to precision weaponry. On the plus side, we have dramatically reduced collateral damage, and our use of stealth and precision weapons in the first Gulf War quickly led to overwhelming victory. That has informed the technological and geopolitical ambitions of Russia, China, Iran, and North Korea for 30 years. And at the same time, the ability to target individuals with extreme precision has made it easier for a series of presidents to select a strike option from among difficult choices.

It's the old story, the bright and the dark implications of technological advances. Technology's power can lift up our communities, our nation, and our world. That's why we researchers and technologists do this work. This is our extraordinary privilege.

But those advances come only after ethical, smart choices are made. That means we also have some extraordinary responsibilities. One is to bring forth the clearest possible facts about our new technologies, seeing and explaining both their merits and pitfalls. Another is that the weighing of ethics has to start at the start. Even before we know if a technology will amount to anything, the many paths ahead need to factor into research choices: who could benefit, who might control it, can it ameliorate inequity or will it reinforce it? In some cases, we can build better steering mechanisms and brakes into a technology, making that a central design challenge in its own right. The DARPA Safe Genes program has the goal of making gene editing more controllable and even reversible in the event of bioterror or simply bio-error. In data privacy technologies such as those Actuate will use, R&D offers technological solutions that can help with difficult ethical choices.

At Actuate, we want to demonstrate how this mindset, woven into our programs, can be a central feature of a twenty-first century innovation ecosystem focused on societal challenges.

Panaceas are not around the corner. We are in no danger, now or ever, of understanding and solving all of the world's complex problems—especially those involving the most complex elements of all: humans. But new opportunities for making real progress on essential, fundamental challenges are beginning to come into focus. And the resulting shifts in the boundary between tractable and intractable problems will be immensely consequential in improving the lives of many millions or even billions of people. The time to build the innovation ecosystem that can create those opportunities is now.

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