Innovation in Today's Circular Economy
The path forward is combinatorial

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In accordance with the CHIPS and Science Act of 2022, the National Science Foundation (NSF) has requested input on developing a roadmap for its newly established Technology, Innovation, and Partnerships (TIP) Directorate. The objectives are admirable: guide investments aimed at addressing several specific societal, national, and geostrategic challenges, and advance U.S. competitiveness in key technology focus areas; and fund use-inspired research, translation of research results to impact, and educate, train, and develop talent.

This is an important moment. The National Science Foundation has been directed by federal legislation to enter what is largely unfamiliar territory. NSF, which has always focused on basic research, is now charged with working in different terrain, where the focus is on moving science and engineering beyond the laboratory to have the material societal impact we hope for and that our country needs. In my view, this reflects a recognition, even if only tacit, that the conditions under which the United States racked up such tremendous advantages over other countries in the past have changed—and that the change poses a tremendous challenge to the nation.

NSF faces a difficult task. What is required to move thoughts about science and technology, and technologies themselves, into the world to address societal problems is not obvious. The simplistic models long relied on to attempt that transition have created habits and a set of beliefs that do not match current conditions. Putting together a model that can succeed is doable. However, there is an underlying requirement that makes the task even more difficult than it may seem: *breaking away from those habits*.

At the heart of most past approaches that once seemed to work is the central assumption that technology innovation is a *numbers game*. It isn't. However, methods built on that assumption have become so popular that an entire "innovation language" has developed around it, which complicates basic communication about the actual meaning of the words we use to describe the objectives. For example, is black boxing a technology as a pitch for a minimum viable product to investors truly an objective? A necessary step? What do we actually mean by technology? Would a scientist and a businessperson understand the same? Such language that conflates innovation, research, technology, products, and startups adds yet another challenge to the task ahead for NSF. The odds are stacked up against NSF's ability to be able to do something as transformative as the CHIPS Act calls for and be able to communicate it effectively.

This situation truly calls for a new innovation paradigm that I call *combinatorial innovation*, which avoids the rules and stratagem of the numbers game. It makes technology insight a tool, a source of information and intelligence, and an instrument to fuel—in support of NSF's objectives—economic advantage, competitive advantage, national security, and addressing big societal challenges. It is the basis for a roadmap, as NSF seeks to create, that sets out a path that goes in a different direction.

It is a *proven* path, too. MIT iTeams, which I developed and lead at the Massachusetts Institute of Technology, teaches and practices systematic processes to recycle technologies and invent, conceive, and "de-risk" organizations that solve problems with technology. This system brings together *use-inspired* and *translational* research to bridge from fundamental insight to new design requirements and new organizations, has been tested across the globe over the past 15 years, and has been adopted as the basis for venture invention and creation laboratories.

The remainder of this RFI response summarizes this new approach in as simple terms as possible, laying out how it reimagines innovation in the era of the circular economy. It is premised on four key ideas: managing innovation waste; technology repurposing and recycling; creating a feedback loop for innovation; and combinatorial innovation.

Breaking (Bad) Habits

I stated above that most past approaches that worked have assumed that technology innovation is a *numbers game*. By that, I mean that most approaches have assumed that merely accumulating a sufficient amount of "something" will be enough to extract an economic, geostrategic, and even military advantage. When the game began after World War II, we accumulated scientists and engineers, then papers and patents, and then startups, and then rounds of funding per startup.

For a long time, this accumulation "solved" (in a manner of speaking) the problem of moving technological insight to application/use/impact, precisely because the United States maintained an advantage of 20 to 40 years in producing those papers and patents and creating startups—no matter how much went unused or how long it took for impact to materialize. We largely ignored that it took those same twenty to forty years for a new research breakthrough to make it to society, and so the wait has become a truism: when we label a technology "early" or "ready," what that truly refers to in the numbers game is the required time of a process in which a new technology comes to be known and understood by enough engineers and scientists, and then for enough managers and funders with only superficial awareness of the technology to accept it as a "part" in commercial endeavors outside of research. Examples include the vacuum tube, RNA vaccines, PCR, e-commerce, and so on.

That huge U.S. advantage meant we could, as a nation, afford to have inefficient systems. Nearly every "system" built up during this period, up until today, has been predicated on increasing the number of startups and entrepreneurs, based on the belief that the more there are, the greater the odds of finding something that would constitute a breakthrough for society. More recent "methods" based on "failing fast" and "hackathons" and "minimum viable this or that" embrace this same numbers game. It's all a celebration of innovation by *brute force*.

NSF today has an opportunity to move boldly toward a new paradigm for advancing science and technology to societal impact more quickly and effectively—an approach that takes advantage of what makes America unique in the world, especially our *free economy*, which in the numbers game today we fail to use ruthlessly, let alone effectively, for our national benefit.

To reinforce how new this paradigm is, consider the following analogy between moving technology to impact and the transitions from different states of matter. Imagine a world in which our best models for matter only knew of two states: solid and gaseous. In that world, our every idea for how to move substances from one state to the other would amount to what we know in our world as sublimation. We would come to expect a low throughput from one phase to the other under normal conditions, and we would come to accept as different methods fringe work that amounts to strokes of luck and extreme vacuums. We'd be unprepared to consider or leverage intermediate states, triple points, and all other manner of transitional phenomena and points of equilibrium.

That is how we have traditionally worked to move things from the lab into society. Research (sometimes called technology) is the solid; application (sometimes referred to as product or, in the language of this RFI, use-inspired research) is the gaseous state. Innovation is an interface between. The new paradigm I propose and explain is akin to discovering that there's been a whole other state of matter—liquid— between solid and gaseous all along. For innovation that new state is not constrained by discipline like fundamental research is, and it has not been narrowed to a single isolated use. It is a *fluid* state in which technologies can move and react easily.

Stretching the analogy, what makes that new state interesting is that it helps move the discussion away from predicting when a given technology will "sublimate" and into a conversation about the reactions that may occur more easily in a state in which technologies can be more easily reshaped, recombined, and essentially brought to react with one another. That is what I call *combinatorial innovation*, because it avoids the rules and stratagem of the numbers game and it helps create new options from technology—*combinatorially*.

The notion of creating options from technology borrows from a term—Operational Art—used in the U.S. Navy to describe a strategy to ensure victory. According to operational art, winning requires working on continually creating new strategic options while simultaneously reducing the options available to an adversary. This is how the military would seek to create a sustained advantage.

Rather than using technology innovation to create options, the current innovation paradigm constrains progress to technology-capability fits that are "self-evident" and siloed. The challenge ahead for the NSF's new directorate amounts to truly creating an advantage from how we move technology to society. It can start by learning how to create options from technology.

Innovation Waste

Innovation should create options from technology, not reduce them. But today's "innovation paradigm" is reductive and wasteful. An effective innovation organization must have a plan for how to manage all the technologies that were not self-evident, which is the majority, so innovation isn't wasteful.

Traditional approaches to moving technology to impact, and the organizational designs that support them, over-rely on *predicting* solutions (pre-specified applications of research, imagined users). In the commercial world too, the approach is to pre-specify user needs. Established companies and startups alike place disproportionate faith in short-term predictability, resulting in an excess of failed "minimum viable" products, experiments, and services. Their *innovation success* hinges on getting too many things right about 'the idea' at the start, by happenstance. These approaches constrain options at the start, thus reducing the likelihood of successful outcomes—making them hit or miss. All too often, programs end before a technology-capability fit (or a "product-market" fit) has become self-evident, meaning all that effort goes to waste. We call that innovation waste.

This has been the curse of innovation. Organizations tasked with innovation begin by over-constraining the problem with a set of requirements they can use to track "progress." Then, to be efficient, they need the "solutions" they imagined before any innovating actually took place to have been right all along. This systematizes accountability but creates what we call innovation waste. It reinforces the illusion of "safe" technology bets and increases long-term risk. It promotes the false notion that taking technology from research to application is wholly linear, something to be governed solely by progressing linearly along DoD's Technology Readiness Levels.

The buzz around commercial innovation methods conceals another crucial fact: absent active work to clarify the use of a new technology, it takes 20–40 years for new technologies to become clear enough for people to imagine products that would leverage them. Then a significant degree of revisionism (analogous to that described by Thomas S. Kuhn in his famous book *The Structure of Scientific Revolutions*) makes it all look as if it had been self-evident from the start, which doesn't help anyone learn from the unheralded, *real* experimentation that took place in the interim. Consider how, in hindsight, the Internet is generally attributed to DARPA because of ARPANET, which predates it by 20 years, or the claim that the technology for RNA vaccines had been known for more than 20 years. Because of this, mainstream commercial innovation methods are not only linear, but also late. Understanding this will help NSF equip the new directorate with some of the tools it needs to avoid doing the same thing over again.

The typical reaction when innovation waste becomes a problem is to insist on better selection criteria, which limits innovation to ideas that are predictable from the start.

Technology Repurposing and Recycling

Innovation waste further complicates *use-inspired* research. Are we to achieve a use by mere inspection of fundamental research? Or is there a systematic way to find and rescue technologies from oblivion? These questions have been uniquely addressed by our applied work at MIT and elsewhere on what I call "innovation factories," proving a process to systematically recycle and repurpose technologies.

The central tenet is simple: the greatest asset of research and new technologies is that they are malleable—that is, that they are *not* fixed and bound to a specific use and function the way products are—and thus they can be reshaped.

The idea of technology repurposing and recycling isn't new: NASA repurposed Velcro for astronauts; biotechnology reuses knowledge from breweries and fermentation plants; Henry Ford repurposed a technology used in meat packing; and the first laser repurposed a flash lamp and industrial-grade rubies. In fact, one might argue that the very act of innovation starts not with a new idea but with a combination

of repurposed technologies.[1] The novelty at the basis of our work at MIT and around the world is making this a systematic capability.

Technology recycling is easy to grasp and helps make the case for embracing combinatorial innovation.

Technologies initially conceived with a specific purpose in mind (military, carbon sequestration, energy, etc.) may have broader applicability if reshaped (in whole or in part)—including commercial use. But how would these new applications be discovered? How would the old technology be found by those who might reshape it to address a pressing need? What if requirements as specified do not match at the outset? If technology repurposing works for alternate military uses, could it work the same way for dual use? Would recycling technologies lower the cost of discovering requirements and incorporating new technologies? Which organizational design would be needed to address these questions?

Setting out to answer these questions speaks to the roadmap NSF needs—one that would take NSF on a path to lowering the barrier to exploring problems and that would promote a culture of innovation through combination and *STEM literacy* as an asset to understand and ultimately solve problems. It would *increase capacity*, because technology recycling multiplies the use of new, existing, and unmatched technologies to solve new problems, and would result in a *combinatorial explosion of uses*. It would also increase the appreciation for STEM education and the use of *technology as a problem-solving tool*. Combinatorial innovation also offers the opportunity to meaningfully explore dependence on key technologies for *national security*.

The NSF roadmap needs to focus on developing capabilities for this *combinatorial innovation*. NSF investments should go toward creating *access to technology, recycling, and education*. There are innumerable existing technologies sitting unused across our country; let's invest in making them ready for recycling. This can involve populating a technology recycling database, facilitating education, and exploring mechanisms to materialize dual use. And emphasize tools, workshops, and collaboration methods that help technology recycling.

Objective: Build a Feedback Loop

The opportunity is to build an enduring advantage by leveraging several core U.S. strengths that are unavailable to our adversaries: American ingenuity, respect for diversity of purpose, innovation in STEM education, dual use, and a free economy. Specifically, to succeed, the innovation strategy for the new directorate has to empower the free economy by developing a supply of technologies that are made accessible to and playable with to Americans interested in solving problems—and thus give those individuals and groups the opportunity to thrive. The focus on empowering with STEM resonates with current NSF activities, but this focus on empowering enterprising people with access is uncharted territory for NSF, which has always focused on science and to some degree startup contests, but not on equipping problem-solvers to use technology as a tool.

In practice, this means creating a "circular economy" for innovation by introducing a new, systematic capability that redirects what would otherwise be wasted. It would create options from technology and create a sustained advantage from technology repurposing and combinatorial innovation by putting the emphasis on problems and effectively overcoming the bottleneck created by innovation waste. The acceptance of innovation waste (and its analogs such as venture capital's acceptance that 9 out of 10 investments fail) is what has prevented the emergence of a virtuous innovation cycle, a feedback loop.

An analogy to grilling helps explain this point. Current innovation paradigms are akin to cooking a hamburger with the lid of the grill open. It takes longer and more energy to cook that way. A chef might hope for a lone, "disruptive" burst of heat that gets the burger cooked instantly, but that never happens. Close the grill lid, though, and it traps and "recycles" heat. The burger cooks in exponentially less time; there's no need for "disruption."

[1] I discuss this in detail in my book *Innovating: A Doer's Manifesto for Starting from a Hunch, Prototyping Problems, Scaling up, and Learning to Be Productively Wrong* (MIT Press, 2017).

The implications of this analogy are far-reaching. The lid creates a feedback loop that uses what would otherwise be wasted heat to cook a burger in a fraction of the time. Conversely, wasted heat slows cooking. Innovation waste is like cooking with the grill open; it dampens innovation.

NSF's roadmap should aim to develop innovation as a *systematic capability* comprised of approaches for problem exploration, requirement discovery, and technology reshaping, reuse, and recycling. This is how NSF can leverage the U.S. economy and education while helping innovators prosper.

Elements of Combinatorial Innovation

The current context calls for a new structure that views innovation, and more specifically combinatorial innovation, as an operational art. The key elements of combinatorial innovation involve:

- Facilitating innovation experimentation to explore problems with unknown requirements;
- Readying new and old technologies for recycling, repurposing, and reuse;
- Creating options continually rather than searching for sporadic, and singular, "quick wins";
- Complementing and reinforcing existing efforts to promote research or design by requirement;
- Training talent to break with the conflation of innovation with newness or disruption;
- Empowering dual use; and
- Turning technological insight into a strategic capability.

If the new TIP Directorate commits to technology *recycling*, and to *combinatorial innovation* as an operating principle, NSF will make a tremendous contribution to establishing a culture of innovation as a systematic means to bring technology to capability, adapt, and turn dual use into a meaningful tactical, national security, and economic advantage for the United States. The following principles inform how to design a structure that achieves that:

- Success must be measured not in "wins" but in actionable options created.
- Technology recycling unlocks new or old technologies as a source of advantage.
- Bringing forth innovation, at the right scale, requires mechanisms and funding to help entrepreneurs and innovators de-risk their ideas.
- Rather than mimicking today's venture capital industrial complex, the new directorate must level the playing field by warranting viable alternatives for enterprising talent to solve problems with technology. The competition this will create will contribute to decreasing the cost of technology and increasing STEM literacy and access for Americans.

This is an opportunity for NSF to lead the paradigm shift about innovation, especially within U.S. government research agencies, from technology limited to *known* requirements and hopes of disruption to facilitating innovation experimentation with STEM literacy as a tool to manage and overcome uncertainty. NSF could become the first U.S. government agency to systematize the dual-use ideal.

A Critical First Step in Developing the Roadmap

The first step for NSF's new TIP Directorate is to embrace a specific worldview of innovation premised on creating options, making problems tangible, conceiving organizations that solve problems, de-risking them, and recycling, repurposing and sharing what would be innovation waste—so American ingenuity can find ways to solve problems, even those for which directly sponsored TIP efforts may fail to find solutions.

It is a space ripe with opportunities for technology to deliver value, and it is largely unclaimed because almost everyone else is busy *not* making progress in the innovation intermediary culture produced by the last 20 years of linear innovation. In that world, incubators, accelerators, and venture studios all promise to match "ideas" and would-be entrepreneurs for polishing. Startups are the product; return on investment trumps actual problem-solving. Do not take that path.