Character and . . .

Play

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Articles

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Transformative Discovery Science

Character and Play as Key Elements

Adam J. Kleinschmit

Abstract

Play is a central element of curiosity-driven discovery science because it stimulates new ways of thinking and encourages the creative combination of ideas in novel ways. Contemporary scientific culture has evolved to focus on productivity, which often disincentivizes play. Furthermore, the external incentives that drive productivity culture can adversely impact character virtues and lead scientists to compromise their integrity. Holistically, the pressures of productivity slow down the rate of transformative scientific discoveries necessary for innovation, erode trust in our scientific institutions, and dissolve scientific autonomy. Creating greater capacity to unleash the playful spirit of scientists has the potential to strengthen science as an institution and provide tangible benefits for greater societal good.

You enter one of the world's largest professional microbial science meetings. The concourse bustles with groups of international scientists in serious conversation, every fourth person clinging to a telescoping poster tube.

As you walk around, a banner grabs your attention with an elaborate circular reproduction of *The Great Wave off Kanagawa* by Japanese artist Hiroe Nirei. Seemingly out of place, the artwork draws visitors in for a closer look and directs conference attendees to an "agar art gallery," a workshop space for getting creative with microbes. A media relations official explains that the American Society of Microbiology holds an annual art contest to promote a lighter side to its suite of intensive conferences on contemporary research.[1] The "canvas" for this art is the solid nutrient medium housed within a Petri dish that allows for growth of differently colored and textured microbes, creating a living mosaic.

Diverse artwork made with live microbes in a Petri dish

In the workshop space, scientists dip their "paint brush," often just a flat sterile toothpick, into the living "paint" composed of pigmented bacterial cultures. The microbial masterpieces on display vary from reproductions of famous paintings to complex geometric mandalas to anthropogenic scenes. At the exit, a sign indicates that the "agar art" competition pays tribute to the Nobel Prize-winning, Scottish physician and microbiologist Sir Alexander Fleming, discoverer of the antibiotic penicillin, and his playful approach to science.

While occupying only a relatively small, colorful corner of the conference, the agar art highlights a vital yet unappreciated aspect of science—creative play. Playful exploration fosters creativity through divergent thinking. Curiosity guides a scientist into the unknown toward the discovery of fundamental truths about our world, like the discovery of penicillin or the knowledge needed for mRNA-based therapeutics and vaccines. Unfortunately, contemporary scientific culture generates a high-stress environment focused on productivity, which crowds out time for play. The productivity-induced pressure coupled with perverse external incentives too often steers scientists down a dark path. The trend of decelerated transformative scientific discoveries and immoral behavior together diminish the benefits of science for humankind.

The Rise of the Culture of Productivity

WWII Transformed Science

The Second World War (WWII) was largely driven by advances in the development of science and technology, with government funding expanding the scale of what was possible. Almost overnight, science went from a small, tight-knit community supported largely by university budgets to a massive machine kept afloat by government money. Big science generated an amazing array of outputs that transformed the war machine (e.g., atomic bombs). The technical products developed also had a transformative effect on society, including computers, radar, jet engines, influenza vaccines, and the first clinical use of an antibiotic (i.e., penicillin), discovered a decade earlier by Fleming.

After the conclusion of WWII in 1945, Vannevar Bush, scientific advisor to both Presidents Franklin D. Roosevelt and Harry Truman, released his vision of the future for publicly-funded science. In his influential report *Science: The Endless Frontier*, he emphasized that fundamental science, driven by curiosity, is the source for novel scientific ideas and ways of thinking. The body of knowledge it generates serves as the raw material from which applied researchers develop innovations that can transform society.[2] Bush envisioned a sustained, high level of public investment in science, plus the resurrection of researcher autonomy, independent of government, to promote a creative space for scientists. Bush stated, "Scientific progress on a broad front results from the free play of free intellects, working on subjects of their own choice, in the manner dictated by their curiosity for exploration of the unknown."[3] Notice his emphasis on intrinsic motivation, driven by play and curiosity, and its role within the creative process (as with the creation of agar art).

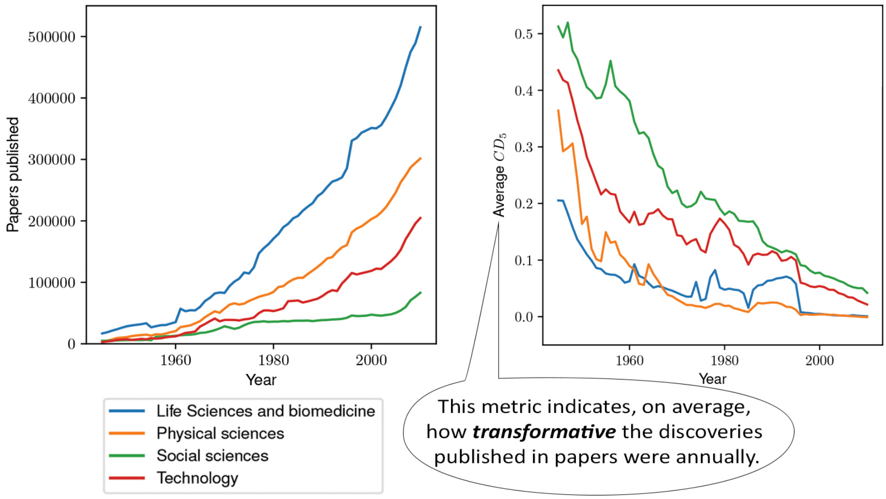
Establishment of the National Science Foundation in 1950 brought to fruition Bush's vision of an expanded investment in science as a public good. This injection of public support for science, which was followed by more funding from other public sources, has since driven an exponential growth in scientific knowledge,[4] but this impressive output correlates with an astounding decline in *transformative* discoveries.[5] A recent analysis of biomedical literature over the past 30 years suggests that instead of branching out into new spheres, scientists are largely asking conservatively narrow questions within well-established fields.[6] Yet transformative discoveries, which challenge our understanding of established science, are important for pushing science and technology in new directions.

Transformative discoveries, which challenge our understanding of established science, are important for pushing science and technology in new directions.

Paradoxically, the focus on narrow questions comes during an era of unprecedented tools and big data sets waiting for us to ask groundbreaking questions previously out of reach.[7] This dynamic contrasts with Bush's desired outcome for the scientific community, suggesting that the current environment suppresses authentic scientific autonomy driven by play and curiosity.

At a Glance:

Numbers of scientific papers published each year compared to how transformative they were

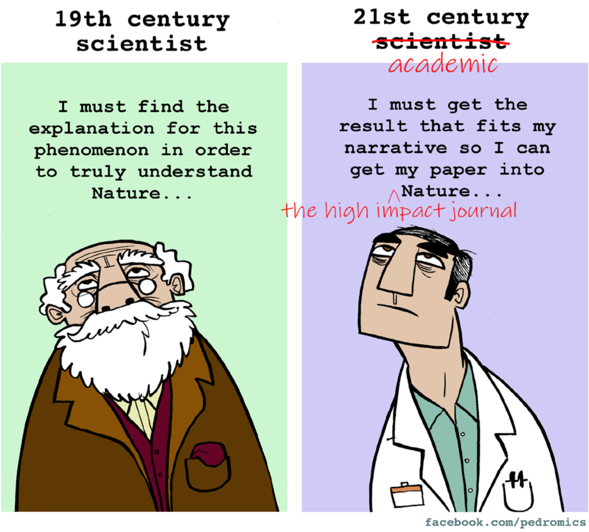


Increase in rate of growth of scientific knowledge with concurrent decrease in rate of transformative *discoveries*
Adapted from Park, Leahey, and Funk, "Decline of Disruptive Science," Figs. 13 and 2.

Productivity Culture Erodes Scientific Autonomy

To make sense of the stark drop in the rate of transformative knowledge and innovation, it is useful to examine post-WWII science. Although interest and engagement in the playful activity of "agar art" remains strong today, the predominating cultural landscape within the scientific community has shifted. Today's scientific enterprise limits playful discovery and forces scientists to produce tangible products in short timeframes.

The shift in expectations transformed the ethic of discovery, which was alive and robust during Fleming's time, into an ethic of productivity.[8] With this moral shift, society has witnessed a change in what validates a scientist's worth. Scientists once vouched for colleagues within a collaborative research group and were driven principally by intrinsic motivation and intuition. The forces that now drive scientific careers are predominantly external, focusing on an individual's productivity metrics (e.g., publications, total grant dollars, citations, patents, journal impact factors). Boosting these arbitrary individual performance metrics can become an end in itself as they dictate career advancement. The pressure wrapped up in productivity culture greatly intensified within the past 50 years and is often summed up in the popular aphorism "publish or perish."[9]



A change in mindset over time in the realm of science
Illustration by Pedro Veliça, facebook.com/pedromics
Commentary in red by Adam J. Kleinschmit

Major changes in the funding of science and its hyper-competitive nature contribute to the shift from an ethic of discovery to an ethic of productivity.[10] Universities have a vested interest in hiring and retaining scientists who can bring in large amounts of money, independent of the quality of science. Grant review panels that decide who to fund are typically risk averse and rate the most feasible proposals as those that should receive merit-based support.[11] In this new system scientists risk not getting funded if they push the envelope too far. The status quo rewards narrow scientific questions, which leads to a steady output of publications but slows the rate of transformative discovery.[12] This culture demands that many scientists compromise their scientific interests to cater to the hottest scientific fields. In the pursuit of productivity, scientific autonomy and the ethic of discovery is suppressed. Counter-productive extrinsic rewards dominate the direction of a scientist's research program and degrade autonomy. External awards replace genuine unbridled intrinsic motivation stemming from the thirst for knowledge and discovery.

A Risk-Taker Despite Productivity Pressure

The COVID-19 pandemic showed the world that scientific risk-takers who do not conform to the pressures of productivity culture sometimes prevail. Public health officials estimate that the rapid development of mRNA-based vaccines during the pandemic saved millions of lives within the first year of availability.[13] Groundbreaking discoveries made decades earlier by curiosity-driven scientists enabled the development of these vaccines within a record time of 11 months. One of these scientists, Hungarian-American biochemist Katalin Karikó, made a key contribution necessary for this technology even though her contemporaries dismissed it at the time of discovery in the 1990s and early 2000s. Karikó and colleagues discovered how to modify synthetic mRNA so that, when introduced into a host as a therapeutic, it would not induce a harmful immune response.[14]

Karikó's story is intriguing because, as a scientist operating within the contemporary scientific ethic of productivity, her scientific interests were viewed skeptically by her peers. Scientists at the time considered her work unrealistic and impractical, as evident by the number of her rejected research proposals. Clearly, her career was doomed unless she pursued an alternative area of science that her peers deemed worthwhile and less risky. Unlike many of her contemporaries, Karikó held steady and refused to give up her research autonomy. This led to multiple academic demotions but, through the support of close colleagues, she managed to continue pursuing her scientific passion for a time as an adjunct professor before moving into industry.

Karikó embodies the virtue of integrity. Arguably, her intrinsic motivation and joy of discovery stemming from internal curiosity have outweighed her interest in external rewards. Her will to continue her research is admirable, given that academic science is a productivity-focused culture. Although productivity may appear to be a laudable objective, adapting one's research interests to appease colleagues undermines creativity and prevents paradigm-shifting discoveries.

This example begs the question of how many other scientists like Karikó were discouraged from following their intuition and consequently never made scientific discoveries that could have transformed humanity. Established scientists have noted that many prominent thinkers, such as British physicist Peter Higgs[15] and English biochemist Frederick Sanger,[16] both Nobel laureates who revolutionized their scientific fields,[17] would not have survived in today's academic system based on their low productivity metrics due to their focus on more difficult problems, which required more scientific risk.

Mural celebrating Katalin Karikó

The Culture of Productivity Provokes Immoral Behavior and Mistrust

The Need for Excellent Moral Character in Science

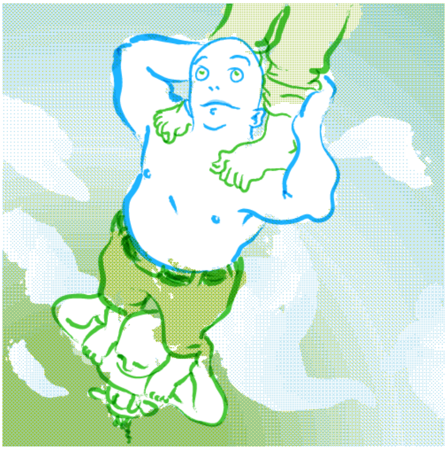
The culture created by the ethic of productivity can challenge (or interfere with the development of) a scientist's character. Intrinsic curiosity and passion motivated iconic scientists like Fleming and Karikó to discover truths about the natural world. They exhibited the foundational virtue of integrity while resisting manipulation by external forces. As the common adage goes, "Integrity is doing the right thing when no one is watching." A more detailed analysis reveals that integrity orchestrates many virtues; thus, it can be thought of as a "meta-virtue" that may direct emphasis onto a more focused character trait in a contextualized manner.[18] For example, a professional scientist of integrity may practice forthrightness in the sharing of findings and the humility necessary to admit error, while at other times demonstrating steadfastness in reporting truth and disclosing potential bias. Whether in the forefront or behind the scenes, scientists demonstrating integrity should be meticulous and transparent with honest intentions and adhere to their commitment to uncovering knowledge.

Law professor Stephen Carter defines a person with moral integrity as having invested the necessary mental energy in discerning right from wrong. When challenged, a person with moral integrity will choose virtuous actions even at personal cost, followed by taking clear ownership of those actions.[19] Collectively, one must be firm in moral principles and the commitment to uphold them even when it is not convenient or comfortable.

How do young scientists develop the character virtue of integrity? Outside of informal mentoring, formal training typically comes through responsible and ethical conduct of research (ERCR) programming. Contemporary ERCR curricula for scientists typically focus on extrinsic rules and legal requirements.[20] Such approaches frame ethics in a negative tone and present it as a hurdle to be overcome. Championing scientific virtues foundational to the spirit of science in formal ERCR curricula[21] would position scientists for thriving with integrity in a culture of discovery and push back against temptations that arise from today's productivity culture.

A person with moral integrity will choose virtuous actions even at personal cost.

The virtue of integrity is essential for maintaining trust for all stakeholders, both scientists and the lay public, and is reached when individuals adhere to accepted standards, professional values, and practices of the scientific community.[22] Integrity ensures objectivity, clarity, reproducibility, and helps prevent scientific misconduct. Scientists must be able to trust the intentions and judgment of their peers and predecessors, as science is grounded in the work produced by others.



Standing on the shoulders of giants

Physicist Sir Isaac Newton famously stated, "If I have seen further, it is by standing on the shoulders of giants." In other words, the intellectual progress of today's scientists relies on embracing the knowledge generated by previous generations of great thinkers. In this context, we see Karikó's humility shine through as she dedicated an individual achievement prize[23] to her colleagues and those that came before her as part of her acceptance speech.[24] Later she stated, "These prizes are mainly important in the way that they put science in the public spotlight and emphasize its importance."[25] Today's scientific community stands on the shoulders of those who came before to make intellectual strides for the public good. Perhaps most importantly, it is notable that the foundation is only as strong as the integrity of the community. Sustained degradation of scientific integrity would inevitably lead to cuts in public support and thus a collapse of the scientific enterprise. Society would lose the many benefits that stem from scientific advances. Perverse behaviors such as scientific misconduct can also change the public perception of science. When people try to politicize bad behaviors especially in the medical sciences it provides fodder for disinformation campaigns.[26]

Immoral Behavior Damages Trust

Contemporary scientific culture encourages careerism, or advancing one's career at the cost of a deeper understanding of natural phenomena and one's integrity. Carefully crafting results by framing a study in a particular light is a survival skill that many protégés learn from their mentors. This mentoring is critical to successful publishing in high impact journals.[27]

Theoretical physicist Albert Einstein's retrospective reflection on a tamer scientific enterprise during his day reveals that productivity culture does little to nurture character virtues.[28] "[A]n academic career compels a young man [scientist] to scientific production and only strong characters can resist the temptation of superficial analysis."[29] Einstein is speaking to what has evolved into the aforementioned "publish or perish" culture, which can challenge the integrity of scientists.[30]

Pressure to focus on productivity metrics challenges a scientist's integrity by prioritizing actions directed at attaining high metrics over the core altruistic reasons (curiosity and thirst for knowledge) to dedicate oneself to science. Within an environment that challenges one's moral being, we see many outstanding scientists leave the field. Perhaps the American psychologist Barry Schwartz states it best when he says, "When you rely on incentives, you undermine virtues. Then when you discover that you actually need people who want to do the right thing, those people don't exist. . . ."[31] For those who do endure the pressure, it is challenging to keep an open, unbiased mind. With a productivity mindset, it is easy to dismiss contradictory evidence while clinging to threads of contentious data that may not be replicable. At its worst, scientists who face immense productivity pressure may be tempted to engage in blatant research misconduct such as data manipulation, fabrication, or plagiarism, which are stark breaches of both intellectual and moral integrity.

Why incentives do not work

A recent poll indicated that over 50% of scientists have changed their behavior in response to the use of productivity metrics, and over 70% of respondents are concerned that colleagues may cheat the system as quantity is rewarded over quality.[32] Reliance on productivity metrics can lead to sloppy science and questionable research practices, including cherry-picking results and use of hyperbole to sell research to prestigious high-impact journals.[33] Furthermore, contemporary scientific culture does not incentivize replication studies or reporting negative results, which erodes scientific integrity and counters the societal scientific goal of establishing truth.[34]

The ethic of productivity can lead to inefficient use of public resources, while damaging trust. Scientists acting without integrity spark fallout from their actions that reverberates through the wider collaborative scientific community[35] and society. The impact in terms of public mistrust of scientific institutions and scientific authority can come with real ramifications for public health such as vaccine hesitancy[36] and beyond. Scientific misconduct can also cause irreparable damage to the psyche and careers of scientific trainees, who represent the future of science. In the early 2000s, developmental geneticist Elizabeth Goodwin pled guilty to committing scientific misconduct after giving in to immoral practices to secure career advancement.[37] This widely publicized breach in scientific integrity made headlines after a group of six graduate students under Goodwin's mentorship turned in their research advisor for deliberate falsification of data. The students grew concerned and lost trust after noticing that portions of a grant application, put together by Goodwin, included data from experiments that had not yet been completed, along with additional evidence of blatant data fabrication.[38]

The ethic of productivity can lead to inefficient use of public resources, while damaging trust.

The implications of this story for science are concerning, but the demonstrated courage of Goodwin's graduate students to stand by their convictions and do the right thing is a virtuous silver lining. These young scientists exemplified Stephen Carter's criteria for integrity: they practiced the active moral reflection necessary to discern right from wrong in this context, acting as whistleblowers and standing up to speak publicly about the situation. The students followed through with their moral commitments at personal cost. The lab was shut down, with the students' financial support thrown into limbo, as it was tied to Goodwin's federal grants. Almost all the students, left with questionable data, were required to start over with new doctoral projects. One of the students was quoted as having lost trust in science at the time.[39] With this emotional and financial baggage, three of the students who had a combined 16 years invested toward obtaining their Ph.D.'s discontinued graduate school. Two others started over on new projects, which prolonged their doctoral studies by years, in addition to feeling the stigma of being connected to a lab with a tainted reputation.[40] As we see in this example, actions by scientists who lack integrity erode the institution of science, a core pillar of society.

Play as an Essential Element in Science

Play Builds Capacity for Curiosity-Driven Science

When the "publish or perish" pressure dial is turned down, scientists have more room for tinkering and play. Play naturally encourages scientists to follow the data wherever it leads, combined with providing opportunities for novel ways of thinking that may foster major breakthroughs. Alexander Fleming, whose playful spirit inspired "agar art,"[41] offers us a useful model of discovery science with integrity through play.

Fleming described his approach to science as "I play with microbes. There are, of course, many rules to this play . . . but when you have acquired knowledge and experience it is very pleasant to break the rules and to be able to find something nobody has thought of."[42] Fleming fully embraced harnessing play to drive his own engagement in science. While tinkering in the forefront of his research field, Fleming used play as a method for serendipitously uncovering interesting things that he could not conceivably predict. Fleming's attitude toward scientific discovery was to play without regard to rules, disciplinary boundaries, and ingrained conventional practices.

The ability to think and act in a playful manner can stimulate new ways of thinking or the ability to creatively combine ideas in novel ways.[43] Play is a way of thinking or a behavior that is characterized by taking place in a protected context, when the subject is in a relaxed state that is intrinsically enjoyable. Play allows for the subject to be open to combining thoughts or behaviors in novel ways and may not appear to have an immediate practical goal.[44] An individual participating in play is more likely to behave or think in a spontaneous and flexible way.[45] In this sense, play may be harnessed as a tool to foster creativity, such as the way Karikó navigated toward using modified mRNA to get past the immune system. Furthermore, the novel patterns of thought stemming from play can transfer to other activities outside of play, often not fully realized until later.

We see a mixing of play and experimental investigation with Fleming at the lab bench. In Fleming's playful campaign to procure microbial isolates for his "agar art," he actively observed old Petri dishes for unexpected outcomes. Fleming coupled this behavior with the mentality of actively foraging for the unexpected, knowing that "chance favours the prepared mind," as famously stated by Louis Pasteur, one of the founding fathers of microbiology.[46] This dictum came to realization and Fleming went on to transform modern medicine after observing that a contaminating colony of mold appeared to inhibit a bacterium he was culturing in the lab. Rather than discard the contaminated plate, he went on to investigate the bactericidal phenomenon, and later described the antimicrobial properties of the extracted "mold juice," naming it penicillin.[47] Penicillin's therapeutic use includes treatment for a variety of bacterial pathogenic infections. One conservative assessment estimates that penicillin has saved more than 10 million lives and paved the way for the discovery of additional antibiotics that have transformed contemporary medicine.[48] Although likely not the first person to observe *Penicillium* inhibiting bacterial growth, his tinkering and curious playful infatuation with microbes led Fleming to fully realize the potential of the antimicrobial compound produced by the *Penicillium* fungus. American zoologist George Bartholomew notably stated, "Creativity often appears to be some complex function of play… related to the exuberant behavior of young animals. The most profoundly creative humans of course never lose this exuberant creativity," an apt description of the relationship between play and creativity that we see in Fleming's work.[49]

Portrait of Alexander Fleming at work/play in his lab

One of Fleming's colleagues reflected at length on Fleming's strategic practice of holding onto old bacterial cultures at his workspace for extended periods of time. Fleming carefully inspected each one for any "unexpected or interesting phenomenon" that might lead to a whimsical investigation in some unexpected direction.[50] In a 1944 portrait by artist Ethel Leontine Gabain, we see Fleming infusing play into his work as he collects a hodgepodge of microbes with a multitude of pigments to function as his expansive artistic palette, arguably a catalyst for discovery.[51] This playful behavior at the lab bench increased the likelihood of stumbling across something meaningful.

Play in science can also present itself in a more subtle way than Fleming's activities. Play researcher and psychiatrist Stuart Brown likens the laboratory work of many scientists to play. Brown came to this conclusion through interactions with French-American Nobel laureate and neuroscientist Roger Guillemin and his colleagues. "When Roger took me through his laboratory he was like a kid as he described his experiments. Here was the biggest, most expensive sandbox he had ever played with, all set up to let him discover wonderful new things."[52] We see this same type of childlike pleasure and excitement in Karikó's reflection on emigrating from Hungary to the United States to pursue a scientific career: "I was not homesick. My home was in the laboratory and as long as I was there, I was happy. . . . [From experimental discoveries] you feel this happiness, the feeling that I understand a piece of nature."[53] Karikó's words capture a glimpse of the joy she experiences through scientific inquiry, akin to children's excitement playing in a playground with so many possibilities at hand.

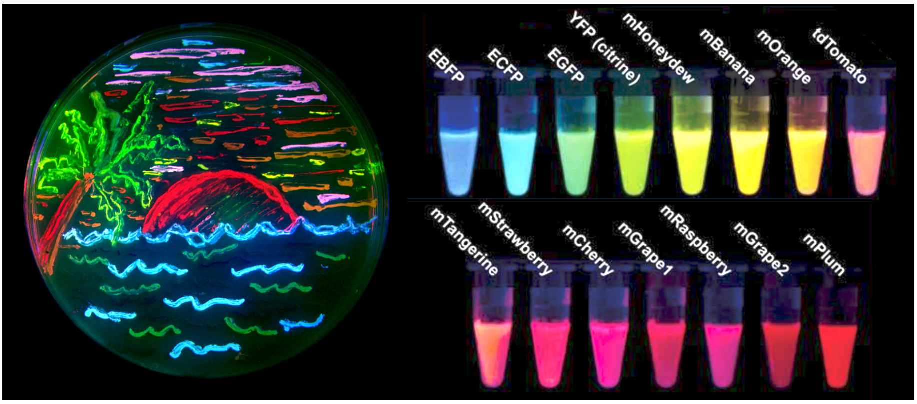
Play is the beginning of knowledge[54]

Fascinated by nature, Karikó found the scientific laboratory to be like a playground from a very young age.[55] If play builds capacity in people to pursue curiosity-driven science, how can society help cultivate a playful approach toward science like we see in Fleming and Karikó? We should harness the natural process of play to teach tomorrow's scientists!

Katalin Karikó with statue commemorating another playful, Hungarian-American scientist, Albert Szent-Györgyi[57]

Any parent can tell you that kids are born curious creatures with an innate drive to explore, tinker, and play with anything in reach. The inquisitive nature that is markedly pronounced in kids is also shared by professional scientists. American astrophysicist and renowned science communicator Neil deGrasse Tyson has spoken extensively on this point, even exclaiming that "Kids are born scientists . . . an adult scientist is a kid who never grew up."[56] As Tyson notes, many scientists are grown-up kids that have never lost their innate inquisitive nature and continue to chase the joy of discovery through curiosity-driven work.

Nobel laureate and American biochemist Roger Tsien notably concocted homemade chemistry sets out of milk jugs and soda cans as a child to playfully experiment with colorful chemical reactions in his backyard.[58] As a professional scientist, Tsien continued his infatuation with colorful compounds and molecules in the laboratory space. Reflecting on Tsien's approach to uncovering groundbreaking ideas associated with fluorescent proteins, a former colleague of his noted that "Roger, in his brilliant ingenuity, figured it should be possible to play with it."[59] These colorful tools would go on to allow scientists to detect proteins in space and time through microscopic imaging and other applications. These tools have transformed our understanding of fundamental cellular and molecular biology, as well as supplied the tools to create vibrant glowing "agar art" using bacteria engineered to produce differently colored fluorescent proteins.



An "agar art" beach scene created in the lab of Roger Tsien with genetically engineered bacteria that express fluorescent proteins, derived from Tsien's Nobel Prize-winning work on creating fluorescent molecules

Taking a cue from the young Tsien tinkering with household refuse to explore chemistry, Tyson encourages parents to support children in the exploration of their environment. Free exploratory play fosters learning through the natural curiosity of kids, especially during developmental years.[60] The power of play has been more formally captured in science education through a variety of distinct but parallel efforts. For example, semi-formal science-learning environments, such as interactive science museums and extracurricular science, technology, engineering, and mathematics (STEM) programming, harness play to teach kids about scientific concepts. In fact, the Iowa Children's Museum is so keenly focused on this mission that it has dubbed its floor staff "Playologists."[61] Makerspaces, also known as "curiosity spaces," are another type of children's venue for hands-on tinkering, inventing, building, and experimenting that promote play.

Extracurricular STEM programming often focuses on hands-on play and inquiry-based experimentation to foster creativity and learning. In some realms, STEM has even expanded to STEAM, with the "A" for "Arts," to incorporate the creative artistic process. An arts-based curriculum focuses on intrinsic rewards arising from play, exploration, risk-taking, problem solving, persevering through failure, and other attributes associated with the creative process.[62]

More formal learning environments, such as schools that implement the Montessori education philosophy, have also adapted play as a tool for learning science and beyond. Montessori schools use playful learning in the form of guided play to encourage hands-on independent learning and provide kids with the choice of what they would like to learn, which involves intrinsic motivation. In fact, educator Maria Montessori, who developed this educational approach, is often credited with the famous quote, "Play is the work of the child."[63] Such environments harness play to tap into the intrinsic motivation of kids to explore and foster divergent thinking. This is in stark contrast to traditional didactic classroom instruction, which is guided by external motivational elements and promotes thinking that conforms to that of the instructor.[64]

Learning through free play

To encourage students to engage in science for the right reasons and appreciating, as Tyson suggests, that trained scientists are kids who never grew up, we should enthusiastically promote structured play in science education (K-18) and in professional curiosity-based science venues. Collectively, we see that play is not only a key element for engaging in scientific education but that it is also harnessed by mature scientists to allow curiosity-driven science to progress efficiently.

Curiosity-Driven Science Spurs Innovation

Stories of Fleming's and Karikó's scientific bench work call up the image of a scientist driven by intrinsic curiosity to play and tinker with their work. Often referred to as curiosity-driven science, but also known by many other monikers (e.g., blue skies, basic, fundamental), this is science under conditions that allow scientists to play and tinker, following wherever the science leads—and often the science leads to discoveries that no one could have predicted. These unanticipated discoveries often radically change the way we think about both established and new frontiers within science. It can be difficult to strategically plan discovery, but it is possible to prepare one's mind to identify rough gems through play that can be polished to yield transformative discoveries. Frequently, the impacts of these fundamental breakthroughs are not fully recognized at the time of discovery, and the societal impact takes decades to come to fruition.[65]

In contrast, applied (also known as translational) research is entrepreneurial in nature, driven by an agenda or a more defined goal. There is a circular relationship between fundamental and applied research, as the latter relies on continuous output from the former to fuel innovations that have direct societal and economic ramifications.[66] Play primes fundamental scientists for creating novel ideas or ways of thinking. As discoveries from creative thinking move into society's knowledge base, innovators can tap into and use them. Innovators refine or transform this knowledge in such a way that it is practical and can be used directly by society.[67]

In Fleming's case, curiosity-driven play led to the discovery of penicillin and the idea that penicillin had the potential to be clinically relevant. Yet it was not until almost a decade later that the importance of Fleming's discovery was fully appreciated by applied scientists who innovatively solved technical challenges to allow for penicillin to directly benefit humanity.[68] This coupled generation and application of creative knowledge became a prototype for future government funding of both fundamental and applied research.[69]

Similarly, Karikó's passionate laboratory play established the knowledge necessary for the development of mRNA-based therapeutics and vaccines, although it was not well received by her contemporaries. Like most fundamental knowledge, Karikó's contributions took over half a decade (after years of skepticism) for its potential to be acknowledged by applied researchers.[70]

The effectiveness of harnessing play to fuel transformative science, coupled with subsequent innovation, has been well documented in the reflections of influential scientists and the tangible products that have arisen from application of their work. In another example of scientific play, British geneticist Sir Adrian Bird commented on his revolutionary breakthrough in understanding epigenetics, a new frontier of research at the time. "I knew I wanted to do something interesting, but I was just playing around more than anything else."[71] Innovations arising from Bird's seminal contributions include genetic testing for Rett Syndrome, an autism spectrum disorder, as well as successful pre-clinical gene therapy as a treatment for the disorder.

In a similar vein, Nobel laureate and American physicist Richard Feynman had an acclaimed playful approach to science that arguably led to some of his most transformative work in quantum mechanics: “Why did I enjoy it [physics]? I used to play with it. I used to do whatever I felt like doing—it didn’t have to do with whether it was important for the development of nuclear physics, but whether it was interesting and amusing for me to play with.”[72] A subset of Feynman’s influential work spurred innovations in nanotechnology and quantum computing, which has yielded the computational power necessary to advance diverse economy-driving fields, from finance to security.

Scientific knowledge is a public good that has historically transformed the fabric of society and continues to influence our quality of life through technology and guiding public policy. Public investment in fundamental science induces a trickle-up effect, encouraging innovation and additional private research,[73] though it may not be immediately realized. Additional examples of this phenomenon include Google and the Internet itself, both of which were originally publicly funded ideas.[74] Each of these examples (i.e., penicillin, mRNA-based COVID vaccines, Internet, Google) was made possible by fundamental science coupled with innovation to transform society.

Considering how transformative discovery science fuels innovation, what can be done to invigorate playful fundamental science?

Considering how transformative discovery science fuels innovation, what can be done to invigorate playful fundamental science? South African geneticist and Nobel laureate Sydney Brenner has championed the idea of dedicating a small slice of all scientific funding to risky projects that encourage play and have the potential to yield big rewards.[75] Extended grant award periods that would provide more breathing room is a complementary approach to stimulate more creative play in science, as longer award durations have been demonstrated to lead to higher-impact scientific work.[76] Alternatively, instead of supporting a subset of scientific work to take on more risk or providing longer production periods, perhaps scientists across the board would benefit from space formally designated for them to explore risky ideas through play.[77] Many technology corporations (e.g., 3M, Google, Adobe) have created a culture supportive of autonomy with protected time and space for play, and have reported capitalizing on these efforts.[78]

Rethinking Productivity and Science

A culture of discovery that embraces the creative process and relies less on arbitrary metrics, being instead based on judgement of peers who are not swayed by the demands of productivity culture, imperfect though they still may be, would grow both intellectual and moral integrity in place of behaviors that erode the integrity of science.

Free play is the cornerstone for generating knowledge, including that which flows out of curiosity-driven scientific research teams. Within this creative experience it is important for play to take place in a protected environment that allows the scientist to tinker and explore without negative consequences. Structural institutions that dictate how scientific inquiry is funded and which projects are supported should re-invest in promoting play.

Transformative curiosity-driven science is rare, as recent scientific findings do less to push science and technology in new directions. Instead, the focus on "safe" research questions fills in small holes in society's body of scientific knowledge through incremental advances. It does not make sense to have all of society's scientists collectively participating in relatively conservative research. Rather, there is value in promoting scientists who chip away at the line demarcating the realm of the unknown. Perhaps play can set the stage for paving new ways of thinking and innovating. Scientific policy coupled with scientific virtue training that cultivates space for more play has the potential to allow scientists to reconnect with their passion for discovering truth, stay true to their ideals, and allow for transformative discovery science to blossom.

Perhaps play can set the stage for paving new ways of thinking and innovating.

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(CUREs), and education research. When not tinkering in the laboratory he enjoys playing with family and curling up with a good book late in the evening.

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Notes

1. Madhusoodmanan, "Petri Palettes."
2. Botstein, "More Basic Biology Research."

3. Bush, *Science: The Endless Frontier*, 10.
4. Bornmann and Mutz, “Growth Rates.”
5. Park, Leahey, and Funk, “Papers and Patents.”
6. Rzhetsky et al., “Choosing Experiments.”
7. Martynoga, *Molecular Tinkering*, 186.
8. Turner and Chubin, “Changing Temptations.”
9. Edwards and Roy, “Academic Research.”

10. Another science aphorism tightly coupled with “publish or perish” culture is “funding or famine” (see Quake, “Guest Column”) as obtaining funding is critical to support research and allow for generation of publications. Short-term grants directly pay the salaries of the scientists and their personnel, which places the risk on the scientists who propose the research projects. Scientists are also expected to pay the institution to rent lab space. These “indirect costs” may run as high as 50% of each grant secured by a scientist. See Stephan, “How Economics Shapes Science.” The hyper competition has further been fueled by a dramatic influx of young scientists into the pipeline with funding levels flatlining.

11. Grinnell, “Discovery in the Lab.”

12. Professional scientists within this system spend a majority of time in an iterative cycle of writing and administering grants to stay afloat, which also takes scientists away from their creative element.

13. Stuart, “In Gratitude.”
14. Karikó et al., “Suppression of RNA Recognition.”
15. Aitkenhead, “Peter Higgs.”
16. Brenner, “Frederick Sanger (1918–2013).”

17. In the 1960’s Higgs developed a theory about the existence of a subatomic particle that had been the most sought-after particle in physics until it was confirmed to exist in 2012 through experiments using the Large Hadron Collider particle accelerator. Sanger won two Nobel prizes in Chemistry for pioneering techniques to sequence proteins and DNA, respectively. Sanger often talked of his scientific work as “messing around in a lab.” See Brenner, “Frederick Sanger (1918–2013).”

18. Ward and Bryant, “On Regulating Civility.”
19. Carter, *Integrity*, 7.
20. Pennock and O’Rourke, “Scientific Virtue-Based Approach.”
21. Pennock, “Beyond Research Ethics.”
22. Kretser et al., “Scientific Integrity Principles”; Turner, “Science and Integrity.”

23. Having come into the public spotlight in 2020, Karikó has won (often jointly with her colleague Drew Weissman) hundreds of awards including the Lasker-DeBakey Clinical Medical Research Award (regarded as America’s Nobel) and *Time* magazine’s Hero of the Year 2021.

24. *Honoring mRNA Pioneers*, 1:50-2:34.
25. Maurer, “Katalin Karikó.”
26. Boyle, “Americans Distrust Science?”
27. Callier, “Getting Harder to Publish.”

28. During Einstein’s active years, careerism was alive and frequent publishing

influenced career trajectory, but was not at the contemporary level of "publish or perish." Interestingly, Einstein's metrics alone do not paint a picture of one of the greatest scientists of the last century. See Gringras and Khelfaoui, "Why the H-Index is a Bogus Measure." The difficulty of measuring contemporary scientists' impact is further illustrated in that Einstein won the Nobel Prize for discovering the law of the photoelectric effect, but not for his work on the theory of relativity or Brownian motion. See Venema, "Publish or Perish."

29. Clark, *Einstein*.

30. Karikó has also publicly commented on careerism. "You must have a goal as a scientist. It shouldn't be to get a certain tenured position, or other titles, but to really research and understand a detailed mechanism in a field of science. This is something that a lot of people get wrong. If you publish papers—more is better—it can help you get a promotion, more grants, a larger team. However, if another scientist scoops you by publishing something similar like what you were working on, you feel devastated. If your goal is purely scientific, you will not be upset, instead rather happy that there is more data and maybe you will even get validation for your theory. But when I talk to other scientists, the reality is, that most are upset if somebody publishes anything before them." See Maurer, "Katalin Karikó."

31. Zetter, "TED: Barry Schwartz."

32. Abbott et al., "Do Metrics Matter?"

33. Smaldino and McElreath, "Natural Selection."

34. Ioannidis, "Published Research Findings."

35. French Neuroscientist Sylvain Lesné, the first author on one of the most cited Alzheimer's studies over the past 15 years, has been accused of doctoring data in this and over 20 other bodies of work. See Piller, "Potential Fabrication." Scientists within the same field have stated their inability to replicate Lesné's findings and have been skeptical of his work for years. See Grimes, "What an Alzheimer's Controversy Reveals." This exemplifies a poor public investment of millions of dollars, as many of Lesné's colleagues in the Alzheimer's research community choose to ignore his work while others rely on trust, despite the fact that his work is likely flawed, and base the foundation of their research off of his, leading to a secondary waste of resources.

36. Former British physician-scientist Andrew Wakefield (now discredited and disbarred) falsified data to make an invalid connection between autism and the measles, mumps, rubella vaccine in a prestigious medical journal. Wakefield's self-delusional and retracted work continues to be the basis of misinformation campaigns and has been cited as potentially the most damaging medical hoax of the past century. See Flaherty, "Vaccine-Autism Connection."

37. Couzin-Frankel, "Scientist Turned in By Grad Students."

38. Couzin, "Truth and Consequences."

39. Zimmer, "Research Misconduct."

40. Couzin, "Truth and Consequences."

41. Dunn, "Painting with Penicillin."

42. Maurois, *Sir Alexander Fleming*, 211.

43. Bateson and Martin, *Play, Playfulness, Creativity and Innovation*, 4, 5, and

chap. 5.

44. When play is combined with a particular positive mood state (i.e., playfulness), the resulting construct can be described as playful play. See Bateson and Martin, 2. Throughout this article, "playful play" is denoted simply as "play."

45. Bateson and Martin, 8–9, 43–45, 57.

46. Maurois, *Sir Alexander Fleming*, 204.

47. Fleming, "Antibacterial Action of Cultures."

48. Kardos and Demain, "Penicillin."

49. Bartholomew, "Scientific Innovation and Creativity."

50. Maurois, *Sir Alexander Fleming*, 109.

51. Root-Bernstein and Root-Bernstein, *Sparks of Genius*, 248.

52. Brown, *Play*, 63.

53. *Katalin Karikó*, 1:08-1:44.

54. Quote widely attributed to American anthropologist George Dorsey

55. Nair, "QnAs."

56. *How to Raise Smarter Children*.

57. Colleagues described Nobel prize-winner Albert Szent-Györgyi as having an intuitive, playful approach to scientific questions. See National Library of Medicine, "Albert Szent-Gyorgi". Fittingly, he was also concerned that those exploring the fringes of science received less support for their research. See Szent-Györgyi, "Dionysians and Apollonians."

58. Wang and Aamodt, "Play, Stress, and the Learning Brain."

59. Chang, "Roger Y. Tsien."

60. Van Schijndel et al., "Preschoolers"; Cook, Goodman, and Schulz, "Where Science Starts."

61. Vogler, "Fun with Science."

62. Perignat and Katz-Buonincontro, "STEAM in Practice and Research."

63. Armitage, "Play."

64. Rogoff et al., "Organization of Informal Learning."

65. Botstein, "More Basic Biology Research"; Cadogan, *Curiosity-Driven "Blue Sky" Research*.

66. Henard and McFadyen, "Complementary Roles."

67. Bateson and Martin, *Play, Playfulness, Creativity and Innovation*, 3.

68. Howard Florey, Ernst Chain, and colleagues adapted Fleming's idea and worked to identify a more potent strain of *Penicillium*, streamlined the extraction process, and worked out how to scale up and test the substance on human subjects. See Bernard, "How a Miracle Drug Changed the Fight."

69. Kardos and Demain, "Penicillin."

70. Garde and Saltzman, "Story of mRNA."

71. Gitschier, "On the Track of DNA Methylation."

72. Feynman and Sackett, "Surely You're Joking," 157.

73. Sussex et al., "Quantifying the Economic Impact."

74. Hart, "Brief History"; Hart, "On the Origins of Google."

75. Dzeng, "How Academia and Publishing are Destroying Scientific Innovation." Most public and private funding agencies supporting science do not tolerate risk as

they prioritize funding proposals that aim for incremental advances. Might it be wise to think about these pots of money as an investment portfolio supporting societal scientific advancement? Any financial planner worth their salt would red flag an undiversified portfolio fixed exclusively with conservative investment instruments. Calculated ventures to support high risk/high reward science would be a good investment for society and could avoid stifling the creative nature of play.

76. Azoulay, Graff Zivin, and Manso, "Incentives and Creativity."

77. This includes space to branch out and learn about other scientific fields or tools outside of one's narrow scientific specialty to stimulate creative thinking to encourage polymath versus specialist behavior. See Root-Bernstein, "Life Stages."

78. These private sector efforts nurture and encourage people to pursue passion projects that rely on intrinsic motivation even if considered high risk/high reward. Google founders Larry Page and Sergey Brin have explained this approach to stakeholders by stating, "This [20% rule] empowers them [employees] to be more creative and innovative. Many of our significant advances have happened in this manner." See Page and Brin, "2004 Founders' IPO Letter." Google has emphasized the creative impact and magnitude of the return stemming from its cooperate investment in creating a safe play for play.

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