2017

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This is the author's accepted manuscript version of a work that was accepted for publication in Physics of Fluids 29, 020602 (2017). The final publication is available at http:doi.org/10.1063/1.4974531

In Defense of Science: What Would John Do?

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(Dated: 8 August 2016)

Recent onslaughts on the importance of pure research to our collective well-being are trending. In this essay, I discuss the issues involved and offer a rebuttal. The thoughts are inspired by my mentor, academic sibling, and idol John Leask Lumley.

PACS numbers: (47), (68)

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I. INTRODUCTION

The ultimate goal of research and development is to produce new or improved products. To stay competitive, companies allocate a portion of their resources to R&D. That portion is typically considerable for startup and high-technology firms. For example, the iPhone arguably propelled Apple to become the largest company in the world by market capitalization. Governments also support R&D for such purposes as better crop yield, medical advances, weaponry, space exploration, energy resources, and clean environment.

The R in R&D is broadly divided into applied research and basic research. The latter is also called fundamental, pure, or curiosity research. This type of research improves our understanding of the natural world. Curiosity research rarely pays immediate benefits, and therefore is supported mostly by the taxpayers. In the long term, however, fundamental research forms the foundation for applied research, onto the development of commercial products, and ultimately better living standards.

As a rule of thumb, if the development of a prototype costs \$100, then applied research toward the same product costs \$10, and pure research costs a meager \$1. That modest cost comes at a price: pure research does not often transition to a product, and spectacular long-term successes are not the norm. Basic research is a risky business; nevertheless it is one of the better things of which humans are capable.

A distinguishing characteristic of basic research is its occasional spark to new frontiers unimagined in targeted/translational/applied research. Examples abound: instead of developing a better iron lung, a polio vaccine was discovered; a mold that repelled bacteria led to penicillin; behavior of molecules during chemical reactions resulted in the omnipresent laser; the Internet was a side effect of a Department of Defense's project to develop networks that could survive a nuclear attack; and solving a mathematical riddle metamorphosed into Google. Fundamental research propelled the U.S. to the moon, sequenced the human genome, created global positioning systems, enabled satellite radio and television, and produced magnetic resonance imaging.

For 2011, the United States invested \$405.3B in R&D, more than any other country in the world. But as a percentage of gross domestic product (GDP), the U.S. takes sixth place after Israel, South Korea, Japan, Sweden, and Finland. The situation is more ominous when it comes to the R portion of R&D, particularly the share of basic research. Major events such as WWII, the Cold War, space race, war on cancer, air and water pollution, and energy crisis drove investment in pure research. In the late 1970s, President Carter attempted what President Kennedy inspired in the early 1960s. JFK's 25 May 1961 declaration that the United States should set a goal to land a man on the moon and return him safely to Earth by the end of the decade did succeed. But Jimmy Carter's 7 November 1979 Energy Security Corporation and Synthetic Fuels Program did not. In both cases, basic research was projected to be a significant portion of the corresponding R&D programs. Today, however, federal expenditures in basic science as a share of the U.S. economy (0.82%) are at the lowest level in over fifty years.

A. The Genesis

The 'linear' model of how science drives innovation and prosperity is traced back to the early 17th-century philosopher and statesman Francis Bacon who urged England to catch up with the Portuguese in their use of science to drive discovery and commercial gain. In what is suspected from time to time to be an apocryphal story, Prince Henry the Navigator in the 15th century had invested heavily in mapmaking, nautical skills, and navigation, which resulted in the exploration of Africa and great gains from trade. What is true, however, is that the Prince is credited with initiating the Age of Discoveries, which spanned three centuries.

Fast forward to the twentieth century. In 1945, the MIT scientist/engineer Vannevar Bush issued the report "Science—The Endless Frontiers", which was a blueprint for generous government investment in basic research for generations to come. Sixty-eight years later, the American Society for Biochemistry and Molecular Biology (ASBMB), in cooperation with fifteen partner societies concerned with pure research, issued the report "Unlimited Potential, Vanishing Opportunity". The contrast between the two reports could not be starker.

In commissioning Bush's report, President Franklin D. Roosevelt wrote on 17 November 1944, "New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war [WWII] we can create a fuller and more fruitful employment and a fuller and more fruitful life." Basic research flourished during the following two to three decades, and the United States became a Mecca for scientists from abroad, several of whom went on to become Nobel laureates.

Bush's report resulted in exclusive federal support for the National Science Foundation, National Institutes of Health, and agencies in charge of basic research within the different federal departments. That model for supporting science spread globally, and resulted in rich nations becoming even richer, and several developing countries, e.g. South Korea, Singapore, and Taiwan, joining the world's elite club of prosperous nations. Through heavy investment in academia and research centers, China, for example, leapfrogged ahead of Japan and Germany to become the second largest economy in the world. Causality cannot be proven beyond reasonable doubt, although the preponderance of evidence points to the validity of the linear model (or a version thereof), despite its detractors.

B. The Challenge

Despite all the successes, the linear model has recently been subjected to renewed, unrelenting, trending criticism. The culprits are mostly economists and politicians leaning toward a libertarian philosophy, although an occasional scientist would join the parade. First, does basic research eventually lead to innovation and prosperity? And second, should the central governments be the primary source of funding for an endeavor whose end result is uncertain? In this essay, I discuss the contrarian views and offer a rebuttal. The thoughts are inspired by my mentor, academic sibling, and idol John Leask Lumley, whose life is being celebrated in this special issue of *Physics of Fluids*.

II. THE ONSLAUGHT

Does pure research eventually trickle down to a better standard of living for humans? Most learned persons would agree with that premise, whether the relation is linear or nonlinear. However, that premise, whatever its form, has been challenged by a number of detractors starting in the nineteenth century, although the continual contrarian voices did not have much traction. What put a spotlight on the issue is a recent book[1] by Matt Ridley entitled "The Evolution of Everything—How New Ideas Emerge". As the title implies, the book's author argues that *everything* evolves in a manner similar to biological species. Spurred by the naming of Albert Einstein's two theories of relativity, Ridley titles his thesis

"The General Theory of Evolution", in contrast to Darwin's "Special Theory of Evolution". So, the universe, morality, life, genes, culture, economy, technology, mind, personality, education, population, leadership, government, religion, money, Internet, and even the future all evolve spontaneously, incrementally, gradually, inexorably, and inevitably. Evolution is not a sudden revolution, but rather a cumulative change from a simple beginning. It is a bottom-up, not a top-down, process, which is difficult to dictate or control. Evolution has no need for a grand designer or a creator. The movement is plainly anti-elitist, anti-establishment, and a bit heretical.

A. The Spotlight

The idea is not new, but Ridley's sheer talent, broad intellect, appreciation of history, and superb communication skills drew a deluge of responses and fame. The book was reviewed by many of the world's major newspapers and magazines. The author is a zoologist by training (D.Phil. degree from Oxford), a bestselling author, and he writes regularly for *The Times* (London) and *The Wall Street Journal*. His books have sold more than one million copies in thirty languages. Ridley is also a member of the British House of Lords. Ridley—a denier of anthropogenic climate change—lectured globally on his many ideas and books, including at the Royal Society of Arts in Edinburgh, Google, and the Cato Institute.

B. The Evolution of Everything

On 13 June 1863, Samuel Butler penned an article for *The Press* newspaper (Christchurch, New Zealand) entitled "Darwin Among the Machines". Fast forward to 2000 when Adrian Bejan[2] claimed that all animate and inanimate objects evolve based on a simple law, the Constructal Law: "For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed currents that flow through it." Bejan followed his 2000 book by several others; the latest of the sequence is just published[3] and is entitled "The Physics of Life—The Evolution of Everything". Note that the subtitle of this 2016 book is the same as the title of Ridley's 2015 book,[1] although the two authors do not appear to be aware of each other work, or at least they do not reference each other. Nevertheless, both authors claim to have a theory of everything, something that typically raises my skeptical antenna.[4,5] Is it even a 'theory'? This debate will be kept for another day, and I will now focus on a particular aspect of Ridley's thesis, the evolution of technology. Even that 'smaller' debate may feel like David versus Goliath. My books neither sold one million copies nor translated into thirty languages. I am not even on the top floor of any ivory tower.

C. Science and Technology

My aim in this essay is to focus on a single chapter of Ridley's 16-chapter book, The Evolution of Technology, particularly on his claim that basic research is not needed, at least to the extent commonly believed, for technology to evolve spontaneously, and that central governments should yield most of the funding for such research to the private sector in the form of corporations, think tanks, and philanthropic foundations.

One week prior to the publication of his 2015 book, Riddley penned the essay "The Myth of Basic Science" for *The Wall Street Journal*,[6] in which he essentially provides a preview of Chapter 7 of the book. Riddley uses two other books to support his viewpoint, one by the biochemist turned economist Terence Kealey,[7] and the other by the founding editor of *Wired* magazine, Kevin Kelly.[8] Numerous other references are also cited, including most notably the work of economists known for their libertarian views.

The famed economist Brian Arthur of the Santa Fe institute (previously of Stanford University) wrote[9] that novel technologies arise by a combination of existing technologies and therefore existing technologies beget further technologies. In other words, technology creates itself out of itself. Technology is self-organizing and can, in effect, reproduce and adapt to its environment, just as a living organism would. Steven Berlin Johnson[10] agrees: "The story of technology, like biological evolution, is a gradual but relentless probing of the adjacent possible, each new innovation opening up new paths to explore." The economist Tim Harford[11] points out that trial and error is a tremendously powerful process for solving problems in a complex world, while expert leadership is not. Intelligent design is just as bad at explaining society as it is at explaining evolution.

Ridley[1,6] mentions specifically Thomas Edison's invention of the light bulb: no less than 23 people deserve the credit for inventing some version of the incandescent bulb *before* Edison. Ridley goes on to remind that Elisha Gray and Alexander Graham Bell filed for a patent on the telephone on the very same day. By the time Google came along in 1996, there were already scores of search engines. Kelly[8] documents six different inventors of the thermometer, three of the hypodromic needle, four of vaccination, five of the electric telegraph, four of photography, five of the steamboat, and six of the electric railroad.

Ridley[6] also concludes that if there is no stopping technology, perhaps there is no steering it either. Out with the heroic, revolutionary story of the inventor, in with the inexorable, incremental, inevitable creep of innovation. Ridley challenges the linear model of how science drives innovation and prosperity, and the dependence on taxpayer money to sponsor basic research. He writes:

> Politicians believe that innovation can be turned on and off like a tap: You start with pure scientific insights, which then get translated into applied science, which in turn become useful technology. So what you must do, as a patriotic legislator, is to ensure that there is a ready supply of money to scientists on the top floor of their ivory towers, and lo and behold, technology will come clanking out of the pipe at the bottom of the tower.

Terence Kealey[7] concurs, and states that the linear dogma so prevalent in the world of science and politics is mostly wrong. It misunderstands where innovation comes from, and it generally gets it backward. Kealey regurgitates three old chestnuts:

> When you examine the history of innovation, you find, again and again, that scientific breakthroughs are the effect, not the cause, of technological change. It is no accident that astronomy blossomed in the wake of the age of exploration. The steam engine owed almost nothing to the science of thermodynamics, but the science of thermodynamics owed almost everything to the steam engine. The discovery of the structure of DNA depended heavily on X-ray crystallography of biological molecules, a technique developed in the wool industry to try to improve textiles.

In Kealey's view, and Riddley's acquiescence, technological advances are driven by practical men who tinkered until they had better machines; abstract scientific rumination is the last thing they do. Trial and error is the quickest way to develop new products. It follows that there is less need to fund science from the public's purse; industry will do this itself.

Having made innovations, the private sector will then pay for research into the principles behind them. In those libertarian views, governments cannot dictate either discovery or invention; they should only make sure that they do not hinder it, or crowd out private funds.

All of the above points to a skeptical, even cynical, view of the value of science to advance technology, and to an even more skeptical view of the value of government sponsorship of R&D in general and pure research in particular. My debunking of those ideas follows in the rest of this paper, but first a word about John Lumley.

III. JOHN LEASK LUMLEY

In order to rebut those who undervalue government-sponsored science and its role in enriching our lives, I start by offering a personal view of John Lumley, the legend we honor in this special issue of *Physics of Fluids*. The pious may say, What would Jesus do (WWJD)? As a result of my adulation for Lumley, I ask, What would John do (same acronym)? Here is why I need his perspective.

John Leask Lumley, a first-generation American, had an abiding appreciation of design, encouraged by his immigrant father who was employed as an architectural engineer in Detroit. John's lifelong passion was restoring classical automobiles. Even his beloved golden retriever, Bentley, was named after one of the many models John restored. John's love for mathematics was instilled by his mother whose first job was as a 'human calculator' in a New York department store, despite her eighth-grade education.

At Harvard, John majored in engineering science and applied physics, the closest thing to engineering and design he could find. He then went to The Johns Hopkins University, earning an M.S.E. (1954) in mechanical engineering and a Ph.D. (1957) in aeronautics, both under the supervision of Stanley Corrsin, also a first-generation American. Professor Corrsin was my doctoral thesis advisor a little more than a decade after John left Hopkins to start his career at Pennsylvania State University. In 1977, John moved to Cornell University where he stayed till the end.

Our beloved mentor earned a B.Sc. (1940) in aerospace engineering from the University of Pennsylvania, followed by an M.S. (1942) and a Ph.D. (1947) from Caltech, working under the supervision of, respectively, Theodore von Kármán and Hans Liepmann. The former earned his doctoral at Georg-August-Universität Göttingen under the tutelage of Ludwig Prandtl. Hans Liepmann completed his doctoral studies at Universität Zürich under Richard Bär. One thing in common between the present author, Kármán, and Liepmann is that all three are 'zeroth-generation' Americans.

Shortly after my arrival at Hopkins, I learned of Lumley's many books as well as robust reputation as an expert in turbulence sciences and applications. In 1970 in particular, the draft for John's famed book *A First Course in Turbulence* (with Hendrik Tennekes) was delivered to Stan (by post those days) for his critique. Professor Corrsin was as always very proud of his former pupil, but simultaneously was critical. Lumley's aim was to tackle a 'second closure problem' in turbulence, taking a middle of the road approach between general fluid mechanics books and very-difficult-to-understand specialized turbulence books. John heavily relied on dimensional analyses, asymptotic methods, and rational approximations. But Stan was concerned that John went too far, oversimplifying the complex problem. Over time, it was judged that the teacher was too cautious and the pupil was right: close to half a century later, the book is still used in classrooms worldwide. Despite it all, the relation between the two giants remained cordial, respectful, and strong. Lesson learned.

John Lumley cherished organizing the 'Hopkins Dinner' during the annual meeting of the American Physical Society Division of Fluid Dynamics. His (expensive) taste in food and wine was second to none. If you were fortunate enough to be seated at John's table, you would be assured of a most stimulating conversation on all topics (including for example philosophy of science and technology), a superb meal, and a tab suited for a king.

During one of the APS/DFD meetings, John restlessly listened to a presentation. Lumley was an impatient man and had no tolerance for mediocrity. But when it came time to ask the inevitable question, John said in his typical cynical, sarcastic, endearing way, "I agree with 90% of what you said, but …". Although I do not quite recall what came after the 'but', that casual comment stayed with me decades later, concluding that in science 90% is not good enough. One hundred percent of anything is typically difficult to achieve, but we have to come close to that ideal. Ninety percent is an ocean away from perfection, and John always expected that near perfection. In technology, on the other hand, 90% is quite tolerable and is well within the acceptable margins of a factor of safety, some call it a factor of ignorance.

A. Science vs. Engineering

All of the greats discussed early in this section considered themselves a hybrid engineer/scientist, and that is important to the arguments I am about to make. All believed, or at least were trained to believe, that good basic science is essential to the betterment of technology. All were experts in fluid mechanics, a discipline which—unlike exotic fields such as string theory, particle physics, and astrophysics—can deftly cross the boundaries between pure science, applied science, and technology.

Aside from being an exceptional researcher, Theodore von Kármán was perhaps the most effective spokesperson for science who ever lived. This Hungarian-born, German-educated, universal man with a heavy English accent single-handedly convinced the U.S. Department of Defense to allocate substantial resources for pure research, because that was what was needed to build the strongest military the world has ever known. One of von Kármán's favorite gems was, "The scientist describes what is; the engineer creates what never was". Similar sentiments, for example, "Scientists ask why; engineers ask why not", were expressed by George Bernard Shaw, Albert Einstein, and several others.

There are many scientists and many engineers around the world. But few can claim to be both. That rare breed appreciates the powerful role science plays in developing new and complex technology. John Lumley was such a person, and therefore my remarks in the next two sections are inspired by him. That perspective is different from that of a philosopher, politician, economist, or journalist; merely different, neither superior nor inferior.

I close this subsection with the two-paragraph parting remarks that Lumley delivered[12] as he was awarded the American Physical Society Fluid Dynamics Prize:

> I would like to close with a few words about being a theoretician in the United States toward the close of the 20th century. The United States is a curiously unsympathetic environment for a theoretician, or any scientist interested in fundamental work. We have a sociocultural/historical myth with which those of us who were children here grew up, of egalitarianism, practicality, inventiveness. An American, in this myth, is a man who rolls up his sleeves and pitches in, solving the problem at hand in a clever, simple, practical way (often involving bailing wire and a wad of chewing gum), usually saying over his shoulder that he does not hold with book learning. Edison is often suggested as an example. Many

of our heroes had trouble in school. We tend to regard too much faith in what is written as being a foreign invention. In this environment, the theoretician is viewed with alarm, and felt to be irrelevant. He is regarded as impractical, pie in the sky. It does not help that any theoretician worth his salt can come up with several contradictory theories a day. He had a beautiful theory to explain yesterday's data, but this morning it seems that those data were wrong; this afternoon he has a new theory to explain the new data. Who can trust a man like that?

Despite all that, theory is what gives meaning to observation. Understanding is the process of constructing simple models that explain the observations, and permit predictions. What the theoretician does is a vital part of the loop, and does not receive enough credits here. Our typical reaction to a theory is "let's see some more computations. How does that compare with the data?" Those pragmatic questions are legitimate, and of course, any theory must rush to answer them. However, first the theory exists alone, as an entity in and of itself, and deserves to be appreciated on its own merits. Is it internally consistent, does it connect all the known behavior in a minimalist way? Does it patch smoothly to previously accepted theories? A theory that does all that in an effortless way is often called elegant. Tomorrow, it may be wrong. Even so, it deserves to be regarded as one of the better things of which man is capable.

IV. IN DEFENSE OF SCIENCE

Does science need to be defended? Faced with the deluge of criticism very briefly described in Section II, it does, on two fronts to be discussed in the present section: its usefulness to technology and its source of support. The third front, the pure joy of science, is deferred to the following section.

The difficulty of rebutting the views of Matt Ridley, and the others he relies on to support his believes, is that they are all right in some of what they are professing. I essentially agree with 90% of what they are writing. But according to John Lumley's high standards, 90% is not good enough. This is not unlike trying to debunk a well-woven conspiracy theory, where elements of truths are intermingled with shreds of fantasy to form a reasonable explanation of a real event. In commenting on Ridley's *Wall Street Journal* article, Jack Stilgoe[13] writes in *The Guardian*: "[Ridley] is half-right, and a talented polemicist who is half-right can be a dangerous foe. ... But this complexity should not obscure Ridley's first misstep. The causes of technical and social change are manifold, and scientific research forms just part of the ecosystem, but this doesn't make it inconsequential."

Indeed, many innovations hardly needed much science to emerge, and were essentially developed by trial and error. I can cite many more than what was mentioned in Section II: potato peelers, garden hoses, pens, hoes, cloths and shoes, furnitures, carpets, toys, ... You do not need to agree with Copernicus that the Earth revolves around the Sun in order to construct a decent sundial. And let us not forget the Pyramids and ant colonies, which I refer to as, respectively, Pyramid Engineering and Ant Engineering.

But modern, complex technology requires science to advance. Modern science started with Galileo Galilei (1564–1642) and Isaac Newton (1643–1727), so it is only a little over four centuries old. Obviously, any technology developed prior to that did not have the benefit of modern science. The Pyramids of Giza relied on primitive forms of geometry and astronomy, but for the most part were constructed utilizing the art of trial and error, and of course a colossal supply of labor. The Formicidae did not have even that primitive form of science.

A. Need for Science

Except for some knowledge of lift, drag, and moment as well as conducting primitive wind tunnel experiments, the Wright Brothers' heavier-than-air biplane was for the most part built by trial and error. On the other hand, without the sciences of fluid mechanics, structural mechanics, flight dynamics, control theory, etc., Boeing could not possibly afford the time, or the money, it would take to design, prototype, and construct the Dreamliner. The modern digital computer is based on the ideas of two mathematicians: Alan Turing and John von Neumann. Kealey's[7] claim that trial and error is the quickest way to develop new products is probably true for the potato peeler, but is indefensible for the two examples in this paragraph. Tune in for more.

The laser (light amplification by stimulated emission of radiation) was built in the early 1960 based on the theoretical work of Charles Townes and Arthur Schawlow, itself based on

Albert Einstein's 1917 basic research on spontaneous emission of photons as atoms transition from high-energy to low-energy state. The omnipresent laser is now a multi-billion dollar industry that is firmly grounded in fundamental science. However, nowadays the laser is considered a technological achievement despite its scientific roots. If a scientist uses that technology to advance a new theory or scientific discovery, would we claim that this is an example of technology preceding science, as was claimed in Section II: "When you examine the history of innovation, you find, again and again, that scientific breakthroughs are the effect, not the cause, of technological change." I certainly do not believe so! Yes, there are exceptions, but the "again and again" in that claim qualifies as an overstatement, or, worse, cherry picking.

The miniaturization of the transistor and its successor the integrated circuit is now down to the quantum scale. Moore's law is no accident of evolution. The construction of earthquake-resistant skyscrapers and wind-resistant bridges requires more than Ant Engineering or even Pyramid Engineering, and is firmly grounded in Newtonian, non-relativistic mechanics.

Miniaturization of electronic chips was extended to mechanical components when MEMS (microelectromechanical systems) were developed in the 1990s based on an idea proposed in 1959 by the physicist, and Nobel laureate, Richard Feynman. MEMS led to NEMS, the manipulation of individual atoms and molecules. Nanotechnology involves significant fundamental research, although, for mostly political reasons, the word nanoscience is rarely used. But it is a science, and a multidisciplinary one at that, involving physics, chemistry, biology, and classical and quantum mechanics. In any case, it is absurd to think that either micro- or nanotechnology would evolve by trial and error.

Try to accomplish long- or short-term space travel using trial and error. Not only would we wonder how long it would take to design and construct the spaceship, but also how risky would such an endeavor be? Would either Ridley or Kealey be willing to ride such a vessel? Building the trial-and-error spaceship will be a similar feat to that of a monkey hitting keys at random on a typewriter keyboard and after an infinite amount of time producing the complete works of William Shakespeare. Science drives technology to evolve a great deal faster than biological evolution. The scientific method provides the turbocharged engine to accelerate technology.

The International Space Station, the retired fleet of Space Shuttles, satellites, outer-space telescopes, vessels that made it to the moon or to other planets, were all made possible with deep understanding of orbital mechanics, materials science, flight control, propulsion, aerodynamics, heat transfer, and several other sciences.

Unmanned Aerial Vehicles (UAVs) are now deployed worldwide in the civilian and military sectors, but their genesis is in the 1849 bomb-filled balloons by which Austria attacked Venice. That feat was probably largely accomplished via trial and error, although some knowledge of Archimedes's hydrostatics was surely needed. Modern UAVs, on the other hand, owe their existence to the science of unsteady aerodynamics and the concept of supermaneuverability, which means the ability to maneuver post-stall. The early 1970s concept is due to the German engineer Wolfgang Herbst, PhD, who tragically was killed in 1991 in an aircraft accident. During the 1980s and 1990s, the United States Air Force Office of Scientific Research (AFOSR) and Defense Advanced Research Projects Agency (DARPA) sponsored basic research programs in unsteady aerodynamics, autonomous control, and composites, which eventually led to more sophisticated UAVs, as well as to more maneuverable manned fighter aircraft.

Imagine developing a nuclear reactor or weapon using trial and error. There was not much of that during the Manhattan Project, which employed some of the brightest scientists and engineers on the planet. Fusion is successfully achieved in the stars and thermonuclear weapons, but controlled, break-even fusion is yet to be achieved. Both fission and fusion technologies are grounded in Einstein's $E = mc^2$ and several other sciences. Trial and error were not invited to any of these risky endeavors.

Finally, immunotherapies, targeted and personalized drugs, artificial organs, transplants, medical diagnostic devices, surgical robots, and numerous other medicinal discoveries are solidly grounded in science.

B. Funding Science

The second issue to be addressed in this section involves the funding sources for science. Yes, the private sector would occasionally sponsor pure research. AT&T Bell Laboratories sponsored the groundbreaking research that identified the cosmic microwave background radiation, and further validating the Big Bang Theory. IBM's Thomas J. Watson Research Center sponsored the work that led to dynamic random access memory (DRAM). And the Boeing Research Laboratories supported fundamental research in turbulence during their 1960s quest for a supersonic transport aircraft (SST). But those rare, mostly obsolete examples, are the exceptions that make the rule. Most corporations sponsor applied research and depend on government sponsorship of pure research to feed the pipeline. Long-term basic research with uncertain outcome is too risky for companies whose leaders' jobs depend on the quarterly report. Someone, the taxpayer through their representatives, has to take the long view. Philanthropic foundations, for example the Bill & Melinda Gates Foundation, are typically more interested in translational research.

Kealey's argument[7] that companies make innovations followed by researching the principles behind them may be true in a few rare cases. Yes, science follows technology in some cases, but again that is the exception to the rule. Once a successful product is developed, industry is motivated to do more applied research to improve that product, but has little incentive to discover yet another law of nature to explain the success. Apple is content to use artificial intelligence to make a better iPhone or one of its many apps, but leave the mathematics of AI to academia.

Let us assume Ridley[6] is right to conclude that any regulation of technology is both undesirable and difficult to achieve. His following conclusion that the inevitability of technology means that innovation need not be funded by government is a rather illogical jump, or stretch. The few examples Ridley provides are cherry picking at its best.

To claim that science spending does not correlate with improvements in our standards of living contradicts another book by Ridley.[15] In this 2010 book, he takes us through 200,000 years of human history to make a compelling case that over the millennia poverty declined, disease retreated, violence atrophied, freedom grew, and happiness increased. Ridley argues that 'things' are getting better largely due to market economics and the diminishing role of central planning. He unconvincingly assails creationism in *all* its forms. I agree with some but not all of his heretical dispositions. Surely, there is a happy medium between suppressive, inefficient central planning, à la the communist regimes of Cuba, North Korea, and the now defunct USSR, and the near-complete lack of government interference, à la the laissez-fair policies of Milton Friedman or the utopian libertarianism of such authors as Murray Rothbard[14] or politicians as Ron and Rand Paul.

Did government-sponsored science have anything to do with improving our lives? How about agriculture sciences that dramatically increased crop yield? Health sciences that cured or even prevented numerous diseases? Research in renewable energy that not only reduced our dependence on fossil fuel but also diminished greenhouse gases released into the atmosphere as well as slowed down global warming trends? Even the 'bad' nuclear science that ended World War II or provided mutual assured destruction as a deterrence? It is even called a *theory* of deterrence!

C. The Chestnuts

Four particular examples from Section II deserve their own subsection for rebuttal. It was stated: "When you examine the history of innovation, you find, again and again, that scientific breakthroughs are the effect, not the cause, of technological change. It is no accident that astronomy blossomed in the wake of the age of exploration. The steam engine owed almost nothing to the science of thermodynamics, but the science of thermodynamics owed almost everything to the steam engine. The discovery of the structure of DNA depended heavily on X-ray crystallography of biological molecules, a technique developed in the wool industry to try to improve textiles." Finally, the spotlight was shined on several instances when simultaneous or near-simultaneous discoveries were made in both science and technology, particularly the latter.

First, it may or may not have been an accident of history that astronomy blossomed in the wake of the age of exploration. Some form of astronomical observations always existed. Ptolemy's (erroneous) model of the universe helped sailors navigate the seas for 1,400 years. But it was Hans Lippershey's invention of the telescope and Galileo's improvements followed by the heavenly observations he made that truly opened the science of astronomy in the early 17th century. The evidence-based astronomy pushed aside the divination of astrology. Modern science was born!

Second, the early steam engine did not have the benefit of thermodynamics, but benefited nevertheless from Boyle's law and vacuum science. Later on, the science of thermodynamics showed how wasteful those early engines were. Exploiting the theory of latent heat, the efficiency of the steam engine dramatically improved. So, at a minimum, it goes both ways. To state that the steam engine owed almost nothing to the science of thermodynamics is again an overstatement, a very un-British thing to say.

Third, it is true that X-ray crystallography was developed to improve textiles, but that does not mean that Watson's and Crick's discovery of the double helical structure of DNA somehow follows the improvements in the wool industry. Their research was conducted at Cambridge University's Cavendish Laboratory.[16] It is doubtful that the ensuing scientific revolution would have occurred in the absence of such academic organization. Without the basic sciences of X-rays, diffraction, scattering, and crystallography, the structure of DNA would not have been elucidated. The wool industry's contribution to the discovery of the double helical structure's is at best superfluous.

Fourth, many discoveries (and patents) in both science and technology occurred almost simultaneously. None of that proves one way or the other that basic science does not matter much. So what if there were simultaneous patent applications on the telephone. Or that Boyle and Mariotte discovered the same physical law. Or that scores of search engines preceded Google. Am I missing something? Or are Ridley and Kealey attacking a straw-man version of basic science? The reason for parallel inventions is much simpler than the 'conspiracy theory' being woven: the necessary prerequisite discoveries in basic science and technology had been made, and therefore the near-simultaneous inventions finally were made possible. As simple as that. The ancient Egyptians invented the hoe, but you wouldn't expect them to have invented the laser.

D. Linear Model

As mentioned in Section II, the 'linear' model of how science drives innovation and prosperity is traced back to the early 17th-century philosopher and statesman Francis Bacon who urged England to catch up with the Portuguese in their use of science to drive discovery and commercial gain. The fact that Bacon's views were based on a story related to Prince Henry the Navigator, which may or may not be true, does not disprove that prosperity results from science.

This is how Ridley[6] described the linear model: "You start with pure scientific insights, which then get translated into applied science, which in turn become useful technology." He does not believe this simple model, and I do not either. In fact, not many people seriously believe in the simplistic linear model. There are too many counter flows, sometimes technology follows science, and sometimes it is the other way around. Or neither. Sometimes it takes years for useful technology to come out of science, sometimes it takes decades.

And sometimes nothing practical comes from the end of the pipeline. In short, technology and science grow in several different ways, and their connection is multidimensional—some linearly, some bypassing steps of a linear model, and some proceed in the reverse.

Basic science is hit or miss: one cannot predict what discoveries will or will not be translatable into something useful. What I believe is that a complex relationship exists between science and innovation. Stilgoe[13] asserts that the linear model is lazy story-telling, but the libertarian alternative is far worse. Despite a few lone voices, the vast bulk of work on science policy reach the conclusion that public investments in science 'crowd in', not 'crowd out', investment from other sources. The relation between science and technology is certainly nonlinear and we may never be able to simplify the complex link to a few solvable—at least numerically—equations. There are sudden jumps, sputtering, inverse correlation, etc., to account for the effect of science on technology. Nevertheless, the beneficial effects of science are undeniable.

The U.S. National Research Council issued the 1995 report "Allocating Federal Funds for Science and Technology", which deemed postwar federal research investments spectacularly successful. But the report also questioned the idea that basic research generally leads fairly directly, in a linear fashion, to applied research and then to practical application and commercialization. In other words, while there is no denying of the usefulness of pure research to our collective well-being, the linear sequential view of innovation is simplistic or even misleading. But to take that conclusion and claim that government-sponsored research is a waste of limited resources is, at best, a stretch.

The defense for basic or fundamental research does not need to depend on any particular model. I suspect that Matt Ridley and others set up the linear model as a (second) straw man to debunk the importance of basic science to technological innovation. They are wrong, and smart people can be wrong sometimes.

E. The Pipeline

There is also a tangential albeit important issue in this debate. Does the society need a steady stream of PhDs in all disciplines? If so, who is going to pay for that? The budget of public universities depends in part on state support, and of course on tuition. Private universities depend on their endowments and even higher tuition. Both types additionally need sponsors for their research and graduate programs. This is not welfare for the faculty, as some would claim, but rather an investment in research and graduate students. Is it worthy for the society to sponsor PhDs in science, engineering, and humanities? Market forces generally would prevent overproduction, but at a minimum a steady supply of advanced degrees is needed to keep universities going—not to mention the need to provide a crop of future PhDs for corporate and government research laboratories, think tanks, etc.

F. Engineering Education

In this subsection, we take a brief look at how worldwide institutes of higher education prepare future engineers. Those are the young men and women who will keep the technology engine running ever more efficiently.

Engineering is a human endeavor whose primary goal is to improve the quality of life. Engineers strive for healthier, happier, and more prosperous societies. Modern engineering encompasses three equally important facets: creativity, art, and science.

There are three faces of modern engineering, science being one of the aforementioned triad. But this was not always the case. Millennia ago, the ancient Egyptians built the Pyramids and the Romans constructed a system of aqueducts, long before modern science even existed. Eons before civilization, the purely trial-and-error approach practiced by archaic Homo sapiens when making spears, arrows, and other hunting tools is a manifestation of the engineering art.

Ancient technology had only tenuous links to the science of its times, which was heavily slanted towards geometry and astronomical observations. Modern engineering, on the other hand, deals with much more sophisticated systems and strives to manufacture affordable, competitive, optimized products.

Universities around the world train future engineers in engineering science, with different specialities such as civil, mechanical, electrical, and chemical engineering. There are few engineering technology programs, but those are less common. Ideally, engineering science students have to be grounded solidly in mathematics, physics, chemistry, biology, and similar sciences before learning the art of engineering. In France, for example, engineering college students do not enroll in any engineering classes until the fourth year of a five-year program; the first three years being devoted to the humanities, mathematics, and sciences. Students in the United States start their engineering courses a bit earlier, simply because undergraduate engineering degrees are typically completed in four years.

Starting about two decades ago, pressure to recruit future engineers mounted. In response, the art of engineering was taught at the freshman level, in order to attract, engage, and retain future engineering students who eagerly called for an early hands-on experience. In addition, 'engineering' classes were taught at the high- and middle-school levels. This would be good if it increased recruitment to the ever-expanding engineering colleges.

But all good things have a downside. In most of the above cases, the students were not quite ready to learn science-based engineering. (For example, calculus and calculus-based science come later.) Thus, students are left with the erroneous impression that modern engineering can be learned and practiced without a strong foundation in mathematics and physics.

The delayed shock reaction comes later at a price. When the students are faced with engineering science classes, which are heavily dependent on the calculus-based laws of nature, they howl, "This is not what we signed for". The students wish to continue what they have started, which are to make paper airplanes and engage in egg-dropping and object-catapulting contests. The undergraduates begrudge classes that require them to model, compute, predict, and analyze. Yet, the problem-solving and critical-thinking skills acquired in engineering-science classes are needed to tackle global warming, to provide sustainable energy and fresh water, to erect optimal living spaces, and to create competitive new and improved products from the needle to the airplane.

In summary, what we teach for the most part is engineering science, not engineering technology. Our graduating engineers design and optimize new and improved products using scientific principles, not the trial-and-error approach advocated in Section II.

V. PRIMA FACIE

In this section, we examine the possibility that science is its own reward, whether or not something practical results from it. Homo sapiens lived on this 4.5-billion-year-old Earth for a mere 200,000 years. They were basically hunter-gatherer spending most of their time foraging and reproducing. It is only when agriculture was discovered that, gradually, fewer and fewer people could produce sufficient food to free a portion of the society to pursue other things such as contemplating and philosophizing, preaching and worshiping, teaching and learning, practicing arts and sciences, and enjoying competitive sports as players or spectators. Of course procreation neither stopped nor slowed down. Unlike all other animals, human's ingenuity created more than food and shelter. Science more often than not improves technology, but even if it doesn't, it is there to be cherished, much the same as enjoying literature, painting, ballet, opera, music, and all other high callings of humanity. Like all of those endeavors, science is an acquired taste. A gourmand devours a few hot dogs, but a gourmet savors a few escargots.

A. Robert Wilson's Famed Quote

On 17 April 1969, the physicist and sculptor Robert R. Wilson[17] testified in front of the U.S. Congress Joint Committee on Atomic Energy. The honest exchange between Senator John Pastore and Dr. Wilson about the value of building Fermilab's first accelerator is reprinted below and is telling:

> Senator Pastore: Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?
>
> Dr. Wilson: No, sir; I do not believe so.
>
> Senator Pastore: Nothing at all?
>
> Dr. Wilson: Nothing at all.
>
> Senator Pastore: It has no value in that respect?
>
> Dr. Wilson: It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with those things.
>
> It has nothing to do with the military. I am sorry.
>
> Senator Pastore: Don't be sorry for it.
>
> Dr. Wilson: I am not, but I cannot in honesty say it has any such application.
>
> Senator Pastore: Is there anything here that projects us in a position of being competitive with the Russians, with regard to this race?
>
> Dr. Wilson: Only from a long-range point of view, of a developing technology. Otherwise, it has to do with: Are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about.

> In that sense, this new knowledge has all to do with honor and country but it has nothing to do directly with defending our country except to help make it worth defending.

Those last seventeen words of Dr. Wilson say it all.

B. Universe, Exoplanets, and LIGO

Science is its own reward. The British mathematician G. H. Hardy (1877–1947) had said, "I have never done anything 'useful'. No discovery of mine has made, or is likely to make, directly or indirectly, for good or ill, the least difference to the amenity of the world. . . . Judged by all practical standards, the value of my mathematical life is nil; and outside mathematics it is trivial anyhow. I have just one chance of escaping a verdict of complete triviality, that I may be judged to have created something worth creating. And that I have created something is undeniable: the question is about its value."

In this subsection, we briefly recall three examples of the richness of science: the universe, exoplanets, and LIGO. Questions regarding the universe have been around for eons, and will always be around forever more, at least as long as intelligent life remains. The other two examples, though related to the first, are quite recent.

Every child asks the questions, where did we come from, where are we going, and what is all that around us? Twinkle twinkle little star, How I wonder what you are! Those are the same queries throughout recorded history, but moreover evidence of similar or related questions existed long before civilization. As far back as Homo sapiens existed, evidence of burying the dearly departed with food and clothes were found by archaeologists. With agriculture came more free time to contemplate, and the ancient Egyptians correlated sunrise and sunset with, respectively, the beginning and end of life. The dead merely went to the dark side, but fully prepared for this after life.

The Greek philosopher Aristotle (384–322 BC) believed that the Earth is round and stationary. The Sun, the Moon, the planets, and the stars moved in circular orbits around the Earth. Ptolemy (90–168 AD) elaborated on that idea. The Earth is stationary at the center of the universe, surrounded by eight spheres that carried the Moon, the Sun, the stars, and the five planets known at the time (Mercury, Venus, Mars, Jupiter, and Saturn). To account for the observed complicated paths in the sky, the planets were assumed to move on smaller circles attached to their respective spheres. The outermost sphere carried the 'fixed stars'. For over 1,400 years, that complete albeit erroneous cosmological model helped sailors navigate the seas, although Ptolemy recognized certain flaws in his model. Despite the satisfactory predictions of early astronomy, the epicycles and deferents of the Ptolemaic astronomy made it unnecessarily complicated since it was not based on a correct physical model.

Nicholas Copernicus (1473–1543) turned the universe upside down with his heretical idea that the Sun was the stationary heavenly body and that the Earth orbited around it. A century would pass before Copernicus's model was validated by the two astronomers Johannes Kepler (1571–1630) and Galileo Galilei (1564–1642). Kepler modified the Copernicus's theory so that the planets moved in elliptical—in contrast to circular—orbits around the Sun. Isaac Newton (1643–1727) developed calculus, equations of motion, and universal gravitational theory, all in what is considered the most important single work ever published in physics, *PhilosophæNaturalis Principia Mathematica*. James Clerk Maxwell's (1831–1879) theory of electricity and magnetism completed what we now call classical physics. In biology, Charles Darwin (1809–1882) provided the theory of evolution in his masterpiece "On the Origin of Species".

The Twentieth century brought two theories of relativity, quantum mechanics, the expanding universe, the big bang theory, and many other changes to our understanding of the universe. The sciences of molecular biology, DNA, and complexity advanced our knowledge of all animate objects, and of course of human health.

Our picture of the universe today is rich with 100 billion stars—like our Sun—in the Milky Way, and 100 billion other galaxies, all moving away from each other. Black holes, dark matter, and other unobsevable features complete our view of the 14-billion-year-old universe, at least the one that we know of. Corporations are not rushing to find the answers to the children's questions, especially those asked by extraterrestrial children.

The two additional examples provided in this subsection also illustrate the sheer joy of science. Neither example has any immediate application or provide a clear path to new technology. Our toasters are not going to stop burning our English muffins, our cars are not going to become less expensive or less polluting, and our standard of living is not going to change, at least in the near future. But then again music and other arts are not contributing, directly at least, to those goals either.

In 2016, two significant discoveries illustrate the point of this section. On 10 May 2016, NASA announced the discovery of 1,284 new planets orbiting stars outside our solar system. That is on top of nearly 1,000 previously authenticated exoplanets detected by the Kepler Space Telescope since its launch in 2009. Scientists taking part in the news conference were ecstatic as they announced the biggest planetary collection ever verified in a single swoop.

On 11 February 2016,[18] an announcement was made that gravitational waves (GW) were detected for the first time on 14 September 2015. Using two Laser Interferometer Gravitational-Wave Observatories (LIGO), one located in Hanford, Washington, and the other in Livingston, Louisiana, GW were identified. As part of his century-old general theory of relativity, Albert Einstein predicted the existence of such ripples in the fabric of spacetime. He also cautioned that GW may be too weak to ever be detected. Sixty years later, the idea for LIGO was conceived and construction of the mammoth project was initiated. It took about forty years, more than 1,000 scientists, and $1B to publish a 16-page paper[19] describing the amazing feat of being able to detect the stretching and contracting of space by one part in 10^{21} (10^{-21} is the dimensionless strain in a 4-km long laser beam). That is comparable to the entire Earth expanding by the width of an atomic nucleus. Numerical simulations of the ten field equations of the general theory of relativity indicated that the detected event resulted from the collision of two massive blackholes. In that apocalyptic event, three solar masses disappeared in less than a second and were converted to pure energy in the form of gravitational waves that, traveling at the speed of light, just reached our shores 1.3 billion years later. According to Einstein's famous equation $E = mc^2$, the amount of energy generated during the one-second collision is more than that being generated in any given second by all the rest of the stars in the observable universe.

What kind of species could, should, or is able to accomplish such a feat, with no regard to its immediate applications? In essence, we have opened a new 'telescope' to the heavens. And, we have learned that we can measure length to 1/10,000 the width of a proton. Next on the drawing board is to place in orbit an even more accurate, space-based LIGO.

Both of those slow albeit spectacular successes were government sponsored. Which corporation or philanthropic foundation is capable of investing, or willing to invest, in those pies in the sky!? There is no end to questions that one can ask in science. So, given the finiteness of resources, the society ought to develop a better value system to decide what is worth pursuing. A 'pope of science' in some high-strung place is the wrong approach to that complex issue.

VI. CONCLUDING REMARKS

Inspired by my mentor, academic sibling, and idol John Lumley, I offered in this essay a rebuttal to those who do not believe that science is essential for advancing technology and its resulting prosperity. I argued that central governments and the taxpayers should carry the major burden of supporting pure research. Science not only leads to a better standard of living but also in and by itself is enriching our lives, just as the humanities and arts do. As Dr. Wilson said, It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. And as Dr. Lumley said, [Theory] is one of the better things of which humans are capable. *Scientia est potentia*.

ACKNOWLEDGMENTS

My sincere gratitude to Drs. Robert E. Berger and Michael J. Karweit, two additional academic siblings. Bob alerted me to Ridley's book *The Evolution of Everything*, and shared insightful comments as this essay was being 'evolved'. Mike provided keen historical perspective of the Hopkins zeitgeist. I am grateful to Professors Sidney Leibovich and Katepalli R. Sreenivasan for reading and commenting on the manuscript. Sreeni shared ideas particularly relevant to Section IV D.

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16. The same academic unit where such luminaries as Isaac Newton, James Maxwell, Ernest Rutherford, G. I. Taylor, James Lighthill, and Stephen Hawking practiced their craft.

17. Not to be confused with the astronomer Robert W. Wilson who, together with Arno Penzias, discovered the cosmic microwave background radiation.

18. My birthdate and that of Jennifer Aniston, King Farouk, Thomas Edison, and about 0.27% of all who ever lived.

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