Is the rate of scientific progress slowing down?

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Introduction

Some of the biggest debates over the last decade have focused on the rate of progress, both economic and scientific. As is common in times of economic crisis or slowdown, commentators have focused on what might have gone wrong.

Several individuals have charged that rates of technological innovation are slowing down in the Western world. Silicon Valley entrepreneur and venture capitalist Peter Thiel made one of the biggest initial splashes, by suggesting that the recent contributions of the tech world were considerably overvalued. "They promised us flying cars, and all we got was 140 characters" (stated in various permutations) was his now-famous proclamation. Economist Michael Mandel, then a columnist for *Business Week*, emphasized that rates of productivity growth in the American economy seemed to be slowing, and that this may have contributed to the financial crisis. Tyler Cowen, one of the authors of this paper, published a 2011 bestselling book entitled *The Great Stagnation: How America Ate All the Low-hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel Better*, pushing this issue into the public debate. Later, economist Robert Gordon at Northwestern wrote *The Rise and Fall of American Growth: The U.S. Standard of Living Since the Civil War*, working through the history of American innovation since the nineteenth century. Gordon argued that the innovations surrounding industrialization were unique in their benefits, and that contemporary and even future innovations would never take on a comparable importance. More recently, in the *Atlantic*, Patrick Collison and Michael Nielsen published "Science is Getting Less Bang for Its Buck," focusing more narrowly on progress in science.[1]

Two other developments were underway at the same time.

First, statisticians were finding that some measures of economic progress seemed to be slowing over longer time horizons, especially those of productivity growth. This process culminated in changes at the Congressional Budget Office and the Federal Reserve System, which both lowered their forecasts of future rates of productivity growth, an official recognition that there might be something to these arguments.

Second, a branch of research into science – "the science of science" – accelerated. Researchers in this tradition typically do not focus on economic productivity, but rather they seek to measure the outputs of science more directly. This research might consider the number of papers published, citation practices, what we know about the geographic or age distribution of scientific creativity, or how many scientists it takes on average to produce a new idea.

Our task is simple: we will consider whether the rate of scientific progress has slowed down, and more generally what we know about the rate of scientific progress, based on these literatures and other metrics we have been

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[1] Michael Mandel's writings are mostly no longer on-line, but for one citation see "Official GDP, Productivity Stats Tell a Different Story of U.S. Economy," Seeking Alpha, May 10, 2010. There is also Tyler Cowen, *The Great Stagnation: How America Ate All the Low-Hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel Better*. New York: Dutton, 2011, and Robert J. Gordon, *The Rise and Fall of American Growth: The U.S. Standard of Living Since the Civil War*, Princeton: Princeton University Press, 2017. Finally see Patrick Collison and Michael Nielsen, "Science is Getting Less Bang For Its Buck." Atlantic, November 16, 2018.

investigating. This investigation will take the form of a conceptual survey of the available data. We will consider which measures are out there, what they show, and how we should best interpret them, to attempt to create the most comprehensive and wide-ranging survey of metrics for the progress of science. In particular, we integrate a number of strands in the productivity growth literature, the "science of science" literature, and various historical literatures on the nature of human progress. In our view, however, a mere reporting of different metrics does not suffice to answer the cluster of questions surrounding scientific progress. It is also necessary to ask some difficult questions about what science means, what progress means, and how the literatures on economic productivity and "science on its own terms" might connect with each other.

If progress in science is slowing down, as indeed we have some reason to believe, these data may help us figure out where the problem has come from. We then could act to speed it up, or at least try to figure out how to do so. Scientific progress, in some forms or another, will be required to address problems of climate change, generate output and revenue to solve social problems and pay off government debts, and to address disease, privation, and premature death around the world. If we seek to influence a variable, one of the first orders of business is to perform acts of measurement, based on rigorous conceptualization, and interpret the measures we come up with.

And to the extent that progress in science has *not* been slowing down, which is indeed the case under some of our metrics, that may give us new insight into where the strengths of modern and contemporary science truly lie. For instance, our analysis stresses the distinction between per capita progress and progress in the aggregate. As we will see later, a wide variety of "per capita" measures do indeed suggest that various metrics for growth, progress and productivity are slowing down. On the other side of that coin, a no less strong variety of metrics show that measures of total, aggregate progress are usually doing quite well. So the final answer to the progress question likely depends on how we weight per capita rates of progress vs. measures of total progress in the aggregate. Furthermore, the distinction between aggregate and per capita measures helps us conceptualize what kinds of progress humans have been good at as of late and which kinds not. That may help us to understand and also model the process of scientific progress more generally, and to figure out where the application of new resources is best able to yield additional gains.

This paper is organized as follows. The first section will cover various productivity measures as used by economists. The second section will consider more direct measures of scientific progress, including both inputs for the quantity of science produced, but also numbers on life expectancy, crop yields, and Moore's Law, among other concepts. The concluding section helps interpret the overall results.

I. PRODUCTIVITY MEASURES OF SCIENTIFIC PROGRESS

One major test of an idea or innovation is how well it can be used. Since not all innovations are equally important, and many are hard to track or identify, one attractive way of measuring them is by looking at their expected influence on economic value. In other words, physical or mechanical productivity does not always translate into economic productivity.

Leonardo da Vinci drew out designs for a flying machine in 1485, an “ornithopter” that flapped its wings, inspired by birds—but in practice this “invention” had no practical applications and essentially no impact on society. By contrast, the invention of the heavier mouldboard plough, a less obviously transformative technology, dramatically boosted the productivity of harder Northern European soils in the 9th to 13th centuries, feeding many people and shifting the distribution of urban populations across the continent.[2]

Productivity measures also will direct our attention to the means of spreading scientific improvements. Techniques are useless for most people unless potential users know they exist and understand how to apply them; innovations making spreading ideas easier (such as cheaper paper) may have a significance on a par with the ideas themselves. New processes like planting potatoes or alfalfa clovers could not boost yields if people didn’t know about them. Mass indoor factory production is improved not just by the invention of new machine tools, but also cheaper timekeeping devices, better glass, more efficient whaling, new sources of candle wax, and artificial lighting. Bookkeeping developments, like Fibonacci’s invention of net present value accounting in 1202, can also have massive impacts. The economic productivity-based framework will perform well in picking up and recognizing such points.[3]

A productivity measure avoids much of the potential subjectivity in deciding the importance of new technologies. It is virtually self-evident that productivity has been rising in most parts of the world. Many different data series tell us roughly the same thing: output per capita grows with output per worker and output per labour hour; countries with more of one tend to have more of the others. In the long run all the series are highly correlated with one another. The deeper and tougher question, however, and the one closer to our investigation is whether *rates of growth* for productivity have been rising, stable, or declining. To address that issue, we need to look more closely at what the productivity measures mean and how they are derived. Unlike many of the current debates, however, we do not seek resolution of the issue simply by looking ever more closely at the nature and definition of current productivity statistics. That enterprise, while valuable, is approaching the point of diminishing returns. Instead, we attempt to reinterpret current productivity progress by placing it in a longer historical context. That is, we seek to clear up current debates by “going big” rather than just “looking small.” It will turn out that current disputes about productivity growth in fact reflect some longer standing questions about how to interpret historical progress and economic growth.

GDP as a foundational concept for productivity

[2] On the institutional environment of Britain during the industrial revolution, see Meisenzahl, Ralf R., and Joel Mokyr. "The rate and direction of invention in the British industrial revolution: Incentives and institutions." In *The rate and direction of inventive activity revisited*, pp. 443-479. University of Chicago Press, 2011. On the role of the plough, see Jensen, Thomas Barnebeck Andersen Peter Sandholt, and Christian Stejner Skovsgaard. "The Heavy Plough and the Agricultural Revolution in Medieval Europe."

[3] On early knowledge economies in the Middle East, see Shatzmiller, Maya. *An early knowledge economy: the adoption of paper, human capital and economic change in the medieval Islamic Middle East, 700-1300 AD*. No. 0064. 2015. On agricultural innovation, see Schmidt, Torben Dall, Peter Sandholt Jensen, and Amber Naz. *New crops, local soils and urbanization: Clover, potatoes and the growth of Danish market towns, 1672-1901*. No. 0065. 2014. On the role of innovation in production in Britain, see Kelly, Morgan, and Cormac Ó Gráda. "Adam Smith, watch prices, and the industrial revolution." *The Quarterly Journal of Economics* 131, no. 4 (2016): 1727-1752, as well as Fouquet, Roger, and Peter JG Pearson. "Seven centuries of energy services: The price and use of light in the United Kingdom (1300-2000)." *The Energy Journal* (2006): 139-177.

We will start with the concept of of gross domestic product, or GDP. GDP is defined as the value of the finished goods and services produced in an economy over a particular period of time, often a specified year. In essence, we are taking the quantities for each good and service produced, multiplying those quantities by their respective prices and adding up, as a rough approximation of economic value.

To avoid double counting, only final goods and services are considered. Note that GDP does not count the production of goods and services outside of the marketplace, for instance if you cook a meal in your home.[4] That said, there are independent estimates for "household production" and also the value of leisure time, which can be added to GDP when appropriate. GDP also focuses on measuring flows rather than stocks, so depleting an environmental resource does not per se lower GDP, though it may lead to a lower GDP in future periods, due to the increased difficulty of production if the environmental destruction has negative secondary consequences for the economy. GDP also does not fully measure the bounty of nature, such as when a sunny day makes people happier.

In fact, GDP does not attempt to measure well-being or happiness at all, though to some extent it is correlated with those values. Instead, GDP gives us one handle on how efficaciously human beings can take the material resources at their disposal and convert those resources into useful outputs.

Overall, consider Robert J. Gordon's simple take: "U.S. economic growth slowed by more than half from 3.2 percent per year during 1970-2006 to only 1.4 percent during 2006-2016."[5]

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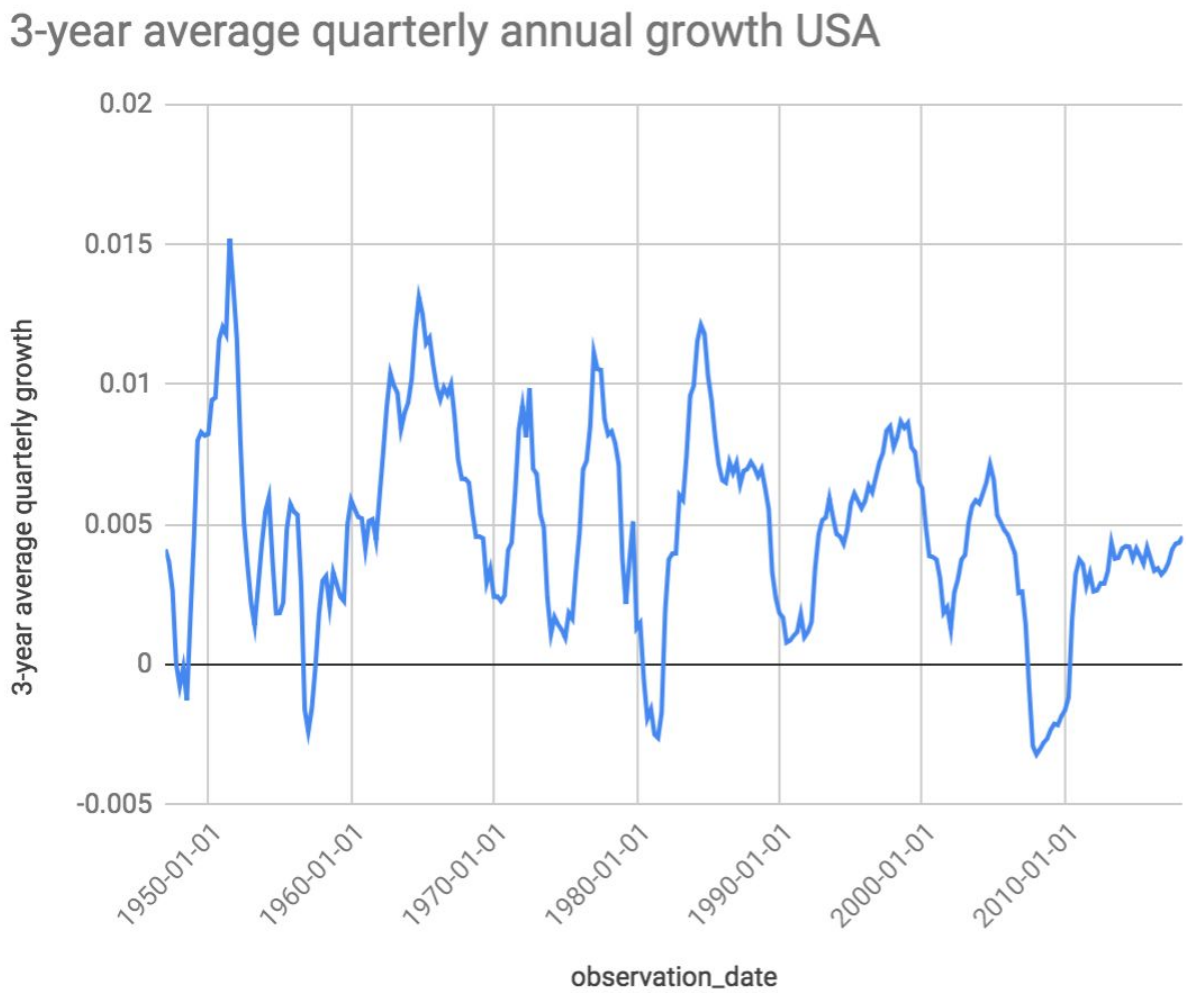
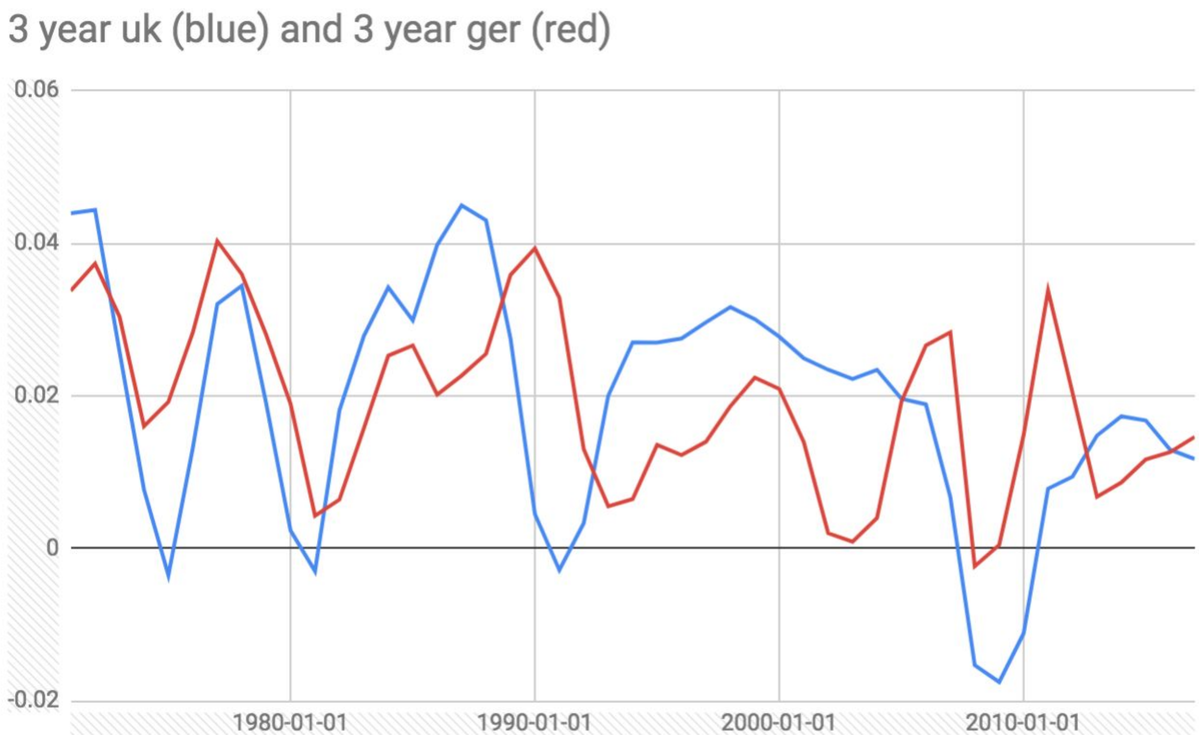
[4] Hence Paul Samuelson's quip (quoted e.g. here Evans, Anthony J. *Markets for Managers: A Managerial Economics Primer*. John Wiley & Sons, 2014.) that GDP falls if a man marries his maid. As for how to define finished goods and services, selling a computer counts as part of GDP but selling a computer chip to a manufacturer does not. It is presumed that the value of the chip will be embodied in the value of the final output. Note also that sales of used goods, and sales of stocks and bonds, are not included in GDP, as they are not considered to add to final value. Yet here you can see some ambiguities in the GDP concept. Real estate broker commissions do count in GDP, but the sale of the house does not. Opinions differ as to whether this is the right approach, but while these many ambiguities do alter the final calculation of the GDP total, they don't change much over time, so they don't substantially affect our judgements of differences between eras.

[5] Gordon, Robert J. "Why has economic growth slowed when innovation appears to be accelerating?" NBER working paper no.24554, April 2018.

Alternatively, if we look at a graph of the three-year moving average growth for GDP per capita for the United States, the numbers again suggest a pretty mediocre story:



We also might consider other OECD nations, for instance Germany and the UK:



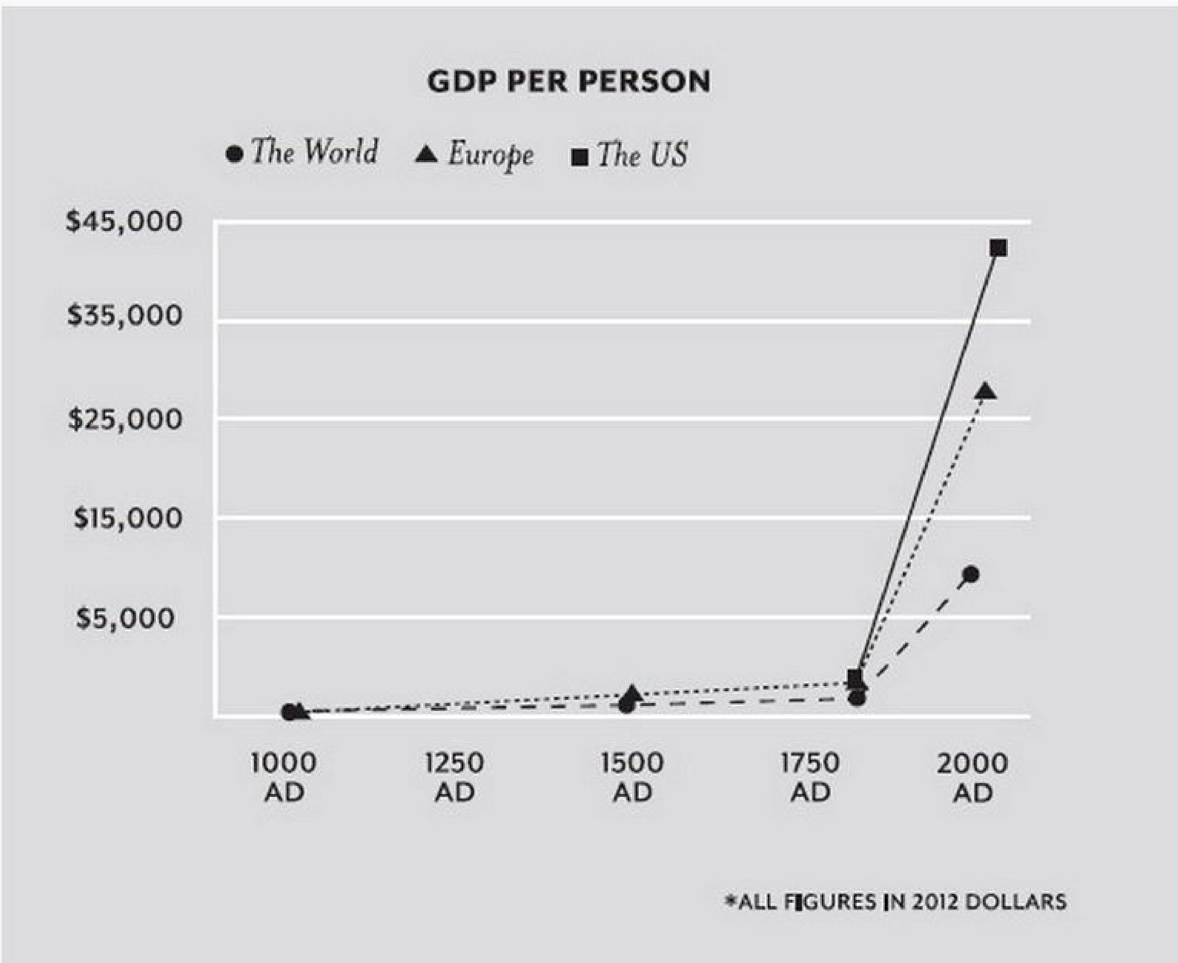
These graphs are showing recent declines in rates of GDP growth per capita, at least in the world's wealthier countries. You will note that such measures often use a moving average of GDP growth, to abstract from cyclical factors of boom and bust present in particular years.

That all said, the GDP-derived measures can be supplemented with appropriate adjustments when needed. In general, neglecting household production overstates GDP growth over the last few decades, as many women have been pulled out of the household into the labor force. For instance, household services were valued at about 37% of GDP in 1965, but in 2017 only at about 23% of GDP, an unmeasured loss. Americans are producing less at home as a percentage of total output, but that does not show up as a GDP loss because the gains from household production were not measured in the first place. In other words, what we know about household production implies the slowdown is probably worse than measured. "Green accounting," which considers the value of the environment, implies a more complex set of conclusions. When it comes to clean air and water, we have been understating progress at least since improvements started in the 1960s, but on carbon emissions and biodiversity the problem has been worsening. We have not seen credible estimates of the entirety of all these effects, but since the loss from diminished household production appears significant, we think it is unlikely that a full incorporation of these harder to measure variables will countermand the implication, found in the raw GDP data, that rates of economic growth generally have been falling. The unmeasured components of GDP probably have experienced subpar rates of growth as well, as is reflected in the common presumption that American family life is more stretched and stressed for many families than in earlier times.[6]

[6] On household production, see for instance Timothy Taylor, "What's the Value of US Household Production," March 20, Conversable Economist, 2017.

That all said, the bigger picture across a much longer time horizon is quite different. It is commonly believed by economic historians that standards of living in early 18th century Europe were not much above those of the Roman Empire, if at all. Obviously exact numbers do not exist, and there are many ups and downs along the way, but the absence of sustained economic growth for millennia is the consensus opinion. The last few thousand years of human history can in fact be described as several thousand years of per capita stagnation, followed by a huge upward burst after the Industrial Revolution. Before the Industrial Revolution, productivity increased well under 1% per year in even the most advanced and successful countries, and with frequent retrogressions due to war, conflict, and plague. Sustained net progress was hard to find, yet since that time, productivity has increased at least 25-fold.

One such portrayal of the data looks like this (with major caveats on any exact numbers in earlier times):



Credit: Economic Growth: Unleashing the Potential of Human Flourishing

Economists sometimes describe this graph as showing the “hockey stick of human prosperity,” and of course it shows a very real breakthrough for human progress. Thus overall history shows many centuries of relative stagnation, a huge burst upwards, and now again a period of somewhat slower growth compared to the early and mid twentieth century, the latter applying to the wealthier OECD economies (we'll consider growth for poorer countries, not on the technological frontier, further below).

Some analysts frame these GDP data in terms of "General Purpose Technologies." A General Purpose Technology (GPT), quite simply, is a technological breakthrough that many other subsequent breakthroughs can build upon. So for instance one perspective sees "fossil fuels," or perhaps "fossil fuels plus powerful machines," as the core breakthroughs behind the Industrial Revolution. Earlier GPTs may have been language, fire, mathematics, and the printing press. Following the introduction of a GPT, there may be a period of radical growth and further additional innovations, as for instance fossil fuels lead to electrification, the automobile, radio and television, and so on. After some point, however, the potential novel applications of the new GPT may decline, and growth rates may decline too. After America electrified virtually all of the nation, for instance, the next advance in heating and lighting probably won't be as significant. Airplanes were a big advance, but over the last several decades commercial airliners have not been improving very much.[7]

At the very least, this kind of hypothesis should be on the table as one possible reason why scientific progress has slowed down, though as we will see later it is not the only possible reason. Furthermore, the GPT hypothesis itself has been questioned. For instance, industries as unrelated to fossil fuels as watchmaking and ship sturdiness became much efficient during the Industrial Revolution.[8] This alternate perspective sees *general* technological improvement, even in such minor ways as 'tinkering', as more fundamental to the Industrial Revolution – and progress since then – as more important than any individual 'general purpose' breakthroughs. Or, if you like, the General Purpose Technology was not coal, but innovation itself.

Total GDP and other total measures of possible import

Let us consider total production or output as a standard of relevance, but along similar lines we might consider total productivity gains or even "total science," or total increases in the quantity of science. Since the general arguments will run roughly in tandem, let us stick with total output for the purposes of the discussion, but the important idea here is the notion of using a "total" to measure progress, rather than focusing only on per capita variables for some subset of the distribution, such as Americans or Westerners or countries on the technological frontier.

A graph for global total output over time looks something like this:

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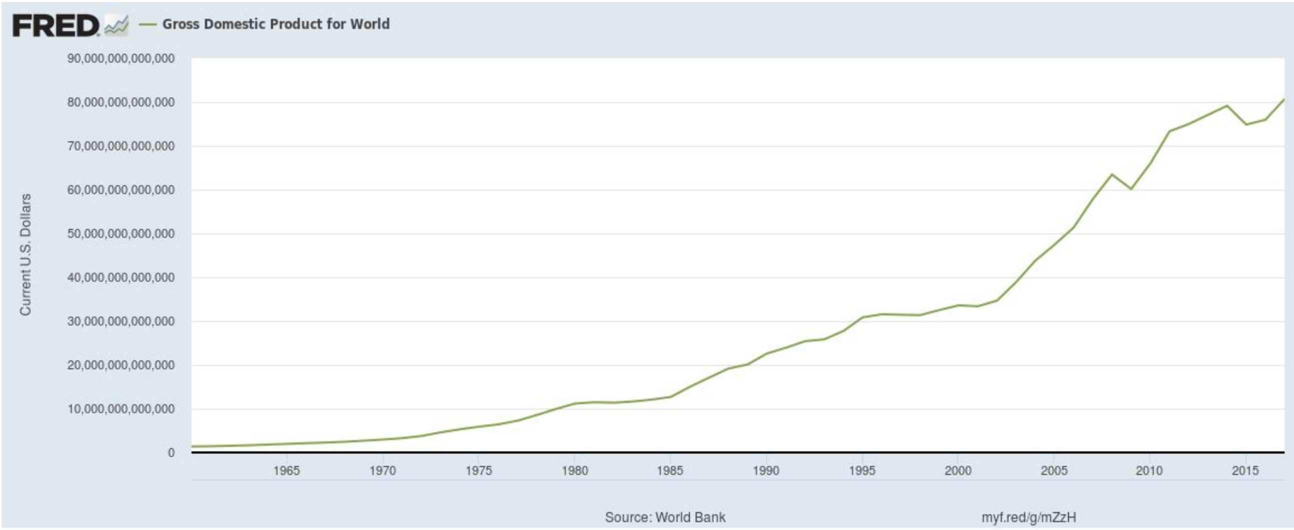
[7] For various perspectives on General Purpose Technologies, see the essays in Helpman, Elhanan, editor. *General Purpose Technologies and Economic Growth*. MIT Press, 1998. For a more recent look as to whether the internet might end up being a new GPT, see Clarke, George R.G., Christine Zhenwei Qiang, and Lixin Colin Xu. "The Internet as a General-Purpose Technology: Firm-Level from Around the World." World Kelly, Bank Policy Research Working Paper 7192, 2015. Artificial intelligence is sometimes another candidate for the next significant GPT.

[8] Morgan, and Cormac Ó Gráda. "Adam Smith, watch prices, and the industrial revolution." The Quarterly Journal of Economics 131, no. 4 (2016): 1727-1752. *and* Kelly, Morgan, and Cormac Ó Gráda. Technological dynamism in a stagnant sector: Safety at sea during the early Industrial Revolution. No. 17/11. Working Paper Series, 2017.



You can see that world GDP has risen from well below $10 trillion in 1965 to over $80 trillion today, an impressive increase over a period of about fifty years. If the standard is total output, total productivity, or total science, progress will measure as never-ending and indeed accelerating, at least up until the recent financial crisis. Obviously, total output keeps on going up, and many other "total" variables, correlated with output, will be rising too, and impressively.

If we consider *rates of change*, rather than just the level of total output, the results still are relatively positive. Total global GDP, in recent times, has been growing in the range of three to four percent a year. It is hard to find reliable numbers for global growth much earlier in history, but it is implausible that the number was in that range or even close. Earlier in history, emerging economies such as China and India performed poorly for many centuries, sometimes even experiencing declines in living standards, such as in parts of the 18th and 19th centuries. At the time, Europe and America often were growing at around two per cent per year, sometimes less, such as during wars. The economic record of Africa in earlier times is hard to measure, but it is rarely suggested that the continent was making the kind of progress we have seen over the last twenty years. In spite of significant data imperfections, it seems clear that the rate of growth for total output—for the world as a whole—has been rising, again with the exception of the slowdown following the recent financial crisis.

There is also good reason to believe that catch-up economic growth has become easier, compared to earlier centuries, and that will help boost total growth. Much of Asia grew rapidly in the post-World War II era, running up through the present day, in distinct contrast with the 19th century. What used to be called "the Third World" is now referred to as "the emerging economies," and not just because of political correctness.

There is corresponding evidence that the global adoption lags of new technologies, across countries, have narrowed. For instance, spindles were invented in 1779 and the mean adoption lag was 130 years (across different countries), railway freight was invented in 1825 with a mean adoption lag of 69 years, and the telegraph was invented in 1835, with a mean adoption lag of 46 years. By contrast, the modern internet had a mean adoption lag of 6 years and the cell phone had a mean adoption lag of 14 years, much shorter time spans.

The more advanced economies tend to be more marked by "intensity of use" for top technologies, rather than simply having them as opposed to not having them.[9]

You might think the various forms of "total" standards are wrong or misleading as metrics of progress, but our goal is not to offer a final normative assessment on which forms of progress should matter most. Quite simply it is a form of progress, call it "progress in the totals only" if you wish. You don't have to see the total variables as the only metric of progress, or to start arguing that we should seek to maximize population. You only have to believe that the total variables should have some weight -- if only for descriptive purposes -- in our final assessment of progress. That said, there are also plausible views (even if you reject them) that supporting more people on earth is in normative terms desirable, and that elevating more people from poverty is a good thing, and so total variables will matter in many normative theories, even if they are not the only conceptions of progress which matter.

That view—some importance for the total in a description of progress—seems modest enough, but it has radical implications. Once we allow total measures in the door, it is much easier to notice progress. For the broader notions of progress, for instance, based on various notions of the total, the world is getting *much* better and rates of improvement are healthy too, for instance as measured by global GDP growth.

But what about the total of science? Is that magnitude going up at higher rates, or is it slowing down, as some of the points later in the paper might seem to suggest? For the time being there exists at least one perspective where the rate of increase of total science -- not to mention the absolute quantity of total science -- is doing quite well.

Consider a reductionist, mono-definitional perspective where all advances in human knowledge are science of some kind or another. Under that premise, arguably the real story of the last few decades has been a growth in social scientific knowledge, most of all in the Asian emerging economies. Furthermore, this knowledge is arguably not mere trickle-down, but rather these emerging economies have found their own methods for making good economic ideas fit their cultures and their polities, and that is a kind of scientific knowledge, broadly construed.

Arguably these new capabilities are mix of a kind of knowledge and also a kind of skill. Many observers will not wish to call them "science." Still, it could be that the world as a whole has been shifting its intellectual resources into the areas where progress is most badly needed, and in some cases that is social scientific knowledge and it is knowledge about how to fit knowledge, and also better institutions, into emerging economies. Under that view of innovation and frontier knowledge, it is again possible to be very optimistic about rates of increase in total knowledge and total output, provided at least we embrace this broader understanding of what progress might be allowed to mean. And if what we are doing is not "science," if it is something "better than science"w at the very least the optimistic perspective still has been rescued.

Again, we are running into the question of what scientific progress is supposed to mean. Under one perspective, drawn from mainstream economics, the current high rate of growth would be attributed to economic "catch

[9] On these adoption lags, more general data, and related matters, see Comin, Diego and Marti Mestier, "If Technology Has Arrived Everywhere, Why Has Income Diverged?" American Economic Journal Macroeconomics, 2018, 10(3): 137-178.

up." That is, countries like China and India adopting many more of the technologies of the West. In this perspective, however beneficial these changes may be, they do not represent scientific progress at all. Scientific progress might be something like "finding a cure for cancer," but "Chinese consumers getting smart phones and Chinese business adopting standard, preexisting accounting and management practices" would fall into a quite different category. This distinction aligns with the one proposed in Peter Thiel's *Zero to One*.[10] In his schema, the world is currently going through lots of 'one to many' improvements: spreading around existing innovations to get richer. But what we usually think of as innovative and scientific breakthroughs are 'zero to one' transitions: something completely new like the mobile phone, the internal combustion engine, or the helicopter.

To be sure, this distinction between catch-up growth and scientific progress is broadly consistent with the ordinary language deployment of the term scientific progress. Still, there is a deeper perspective in which this distinction is not so straightforward. We still have to ask the question of why Chinese catch-up growth is so strong since 1979, and why it was so weak earlier. Obviously, China underwent some series of institutional and political changes, connected with the passing of Chairman Mao and the installation of a more reform-minded leadership, and the finding of formulas to reconcile economic growth with relative political stability. In essence, the new Chinese government (so far) mastered "how to bring in reforms without losing control." That was a kind of advance of social scientific knowledge, whether we classify it as "science" or not. In this regard, improvements in institutions are not so easy to classify, a point we will return to in our discussion of productivity growth in the next section. This take on institutional improvement in fact does not fit easily into the Solow model of economic growth, or with say the notion that China has excelled mainly at catch-up growth rather than innovations. The point remains that few if any of the Western advisors to China had outlined the highly successful path that China has taken. It therefore seems that the knowledge behind the Chinese growth explosion is scarce, rather than well-known, and furthermore no other country has managed to copy the "Chinese model" with comparable success. That seems to make the Chinese experience something different than just pure "catch up" growth.

The focus of this paper is on "scientific progress," but if the world is gaining on the *progress* by giving up somewhat on the *science*, that might itself be a kind of wise scientific decision. Sticking with the narrower concept of science is perhaps not the most appropriate way of interpreting this development, and it might lead us into excessive pessimism.

The less wealthy economies are still engaged in some basic growth activities, such as electrification or building roads and train lines, and so they are receiving relatively high marginal returns and thus higher economic growth rates. Furthermore, they may be adopting some basic techniques of governance, such as basic accountability, use of data, and greater reliance on technocratic expertise. Boosting that spread of governance techniques seems to be one "scientific problem" that the world is actually pretty good at.

So far we have considered one shift of perspective by moving to total, global magnitudes to measure progress. A related perspective shift comes from looking at population changes rather than just per capita variables. Of course in the short run, whether or not we adjust for per capita magnitudes may not matter much, because

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[10] Thiel, Peter A., and Blake Masters. *Zero to one: Notes on startups, or how to build the future*. Broadway Business, 2014.

population does not usually change so quickly. But for broader and longer-term historical comparisons, this becomes an issue and in many comparisons the various magnitudes diverge a great deal with the passage of time.

It is easy enough to see that world population makes major positive strides long before the Industrial Revolution and the concomitant breakthrough in living standards. Consider the aggregate figures for world population, showing of course significant ongoing increases:

Viewed in the context of our discussion, this picture shows that significant forms of progress are possible even when per capita magnitudes such as income are relatively stagnant. Aggregate global population is a steady and then rapid march upwards, even though the story about living standards isn't nearly so simple. Even fairly late into the Industrial Revolution, wages were rising only barely and the main story was one about aggregate numbers. The first seventy or so years of rapid progress in Britain, 1780-1850, led to little or no gain in incomes for the average person. Nonetheless many more people survived who would otherwise have died, and population increase helped to drive big increases in GDP and also general cultural accomplishment.[11]

[11] On living standards in Britain, see Clark, Gregory. "The condition of the working class in England, 1209–2004." *Journal of Political Economy* 113, no. 6 (2005): 1307-1340, noting that this is a controversial view. On population growth, see

We will suggest that in some key regards the new forms of scientific progress are a lot like some of the older, pre Industrial Revolution manifestations of progress, namely much of the progress showing up in the aggregates rather than in terms of per capita percentage rates of growth. Of course eventually economic growth showed up as sustainable in something other than just aggregate population numbers. With the fertility transition, first in France between 1600 and 1800, later in Britain, still later in the USA and Prussia/Germany, and then across the world (it is reaching the least developed countries now), productive gains ceased to translate purely into extra surviving births. Technological progress was so rapid that the maximum population a society could support grew faster than the speed it was having new children, and that translated into a sustained growth in real wages. But that era, although it has become a paradigmatic case study of progress and growth, may be more of an outlier than we think, and that is yet another possible lesson from our investigation.[12]

How much of GDP stems from science?

In any case productivity measures contain a deep flaw for our purposes: many rises in productivity do not come from things we usually consider as "scientific" innovation. For instance, the historiography of both the initial Industrial Revolution itself in the West and the catch-up growth seen especially in Japan, Taiwan, and other locales assigns a major role to institutional and cultural changes. Accounts of income differences between countries often see a large role for institutions as well. At the very least, institutional changes cannot always be directly credited to technological shifts, and instead many institutional changes may be due to social norms, random shocks, luck, or evolution through war, among other factors.[13]

The distinction between economic productivity and scientific progress is easiest to see when natural resources provide a big boost to GDP, for instance in say Norway or Kuwait. Output is produced by combining the three main factors of production: land (which includes natural resources), labor, and capital, and superior endowments of these factors are not identical with progress in science. To be sure, the extraction, transport and sale of oil in Norway *requires* scientific prowess, but the value of the oil is not a very good direct measure of progress in those scientific areas. To some extent, Norway has higher GDP simply because it has more oil. For instance, Norwegian GDP per capita is typically 20-30% above that of Sweden and Denmark, but Norway is accessing the same general stock of scientific knowledge. Similarly, US agricultural productivity per labourer

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Keinan, Alon and Andrew G. Clark. "Recent explosive human population growth has resulted in an excess of rare genetic variants." *Science* 336, no. 6082 (2012): 740-743.

[12] On historical fertility rates, see Brée, Sandra, and David De La Croix. "Key forces behind the decline of fertility: lessons from childlessness in Rouen before the industrial revolution." *Cliometrica* (2017): 1-30. de La Croix, David, and Jacob Louis Weisdorf. "'Decessit sine prole'-Childlessness, Celibacy, and Survival of the Richest in Pre-Industrial England." (2017). Ager, Philipp, Markus Brueckner, and Benedikt Herz. "Structural Change and the Fertility Transition in the American South." (2017), working paper.

[13] On historical productivity figures, see McCloskey, Deirdre N. *Bourgeois dignity: Why economics can't explain the modern world*. University of Chicago Press, 2010. On the role institutions, culture, and genetic in the industrial revolution, see Howes, Anton. "The Improving Mentality: Innovation during the British Industrial Revolution, 1651-1851." (2016), as well as Mokyr, Joel. *The Enlightened economy an economic history of Britain 1700-1850*. Yale University Press, 2010, and Clark, Gregory. *A farewell to alms: a brief economic history of the world*. Princeton University Press, 2008. On institutional change via random shocks, luck, and war, see Mokyr, Joel. *A culture of growth: the origins of the modern economy*. Princeton University Press, 2016. On unevenness of growth, see Robert E. Hall and Charles I. Jones. "Why do some countries produce so much more output per worker than others?." *The Quarterly Journal of Economics* 114, no. 1 (1999): 83-116.

and labour hour outperformed Europe during the 19th and 20th centuries, but some of that gap probably sprung from a high ratio of land to inhabitant, rather than an inherent technological advantage, and for some of that time American science may have been behind that of Europe.[14]

To avoid these kinds of measurement distortions, we might look to a notion of total factor productivity, to which we now turn.

Total factor productivity

Total factor productivity is an attempt to measure overall economic effectiveness: how much a society can do with the inputs it has. TFP, multi-factor productivity, or the Solow residual are all different names for this same concept. It refers to the amount of output growth left unexplained after accounting for all inputs, i.e. it is a residual and not something we measure directly. So if output grew by ten, and the contributions of land, labor, and capital each were judged at 3 (total of 9), TFP would be measured at one. As such, it is vulnerable to measurement errors in any of the main series that go into its calculation. Nonetheless the hope is that this variable measures the "left over" contribution of ideas to the process of production, and thereby helps us measure the efficacy of science. It won't confuse progress in science with a country having a large stock of oil.

One advantage of TFP is that it seems to correspond to common intuitions as to when scientific progress was especially high. Robert H. Gordon, in his book *The Rise and Decline of American Economic Growth*, has argued at great length that scientific and technological progress reached a peak in the early part of the twentieth century. That was a time when fossil fuels, electrification, industrialization, nitrogen fertilizer, cars, radio, telephones, clean water, vaccines, and antibiotics all took on major roles in human lives in the wealthier countries. Within a matter of decades,, human life was transformed, in large part because of the extension and application of the earlier Industrial Revolution. Consistent with this picture, American TFP typically grew quickly in the 1920s and 1930s, ranging from between two to slightly over three percent per year. In more recent times, in contrast, TFP growth often has ranged between one and one and a half percent. The tech revolution has brought some forms of impressive progress, but many aspects of human life are not so different from what we had in the 1960s or 1970s. Cars are better and safer, but those gains are not comparable to replacing horses with cars altogether.

TFP measures also have been improved in recent times. For instance, numerous theoretical and empirical advances reduce the importance of the "residual" objection. Recent improvements allow much closer measurement of factor inputs, accounting for heterogeneous labour value and capital depreciation rates, not just raw totals.[15] They can also track factor utilisation, so we can measure more accurately when fluctuations in output are driven by changes in the work week or how much capital is actually being used. In the below graph, for instance, you can find a standard measure of TFP [labeled as MFP, or multi-factor productivity] from the

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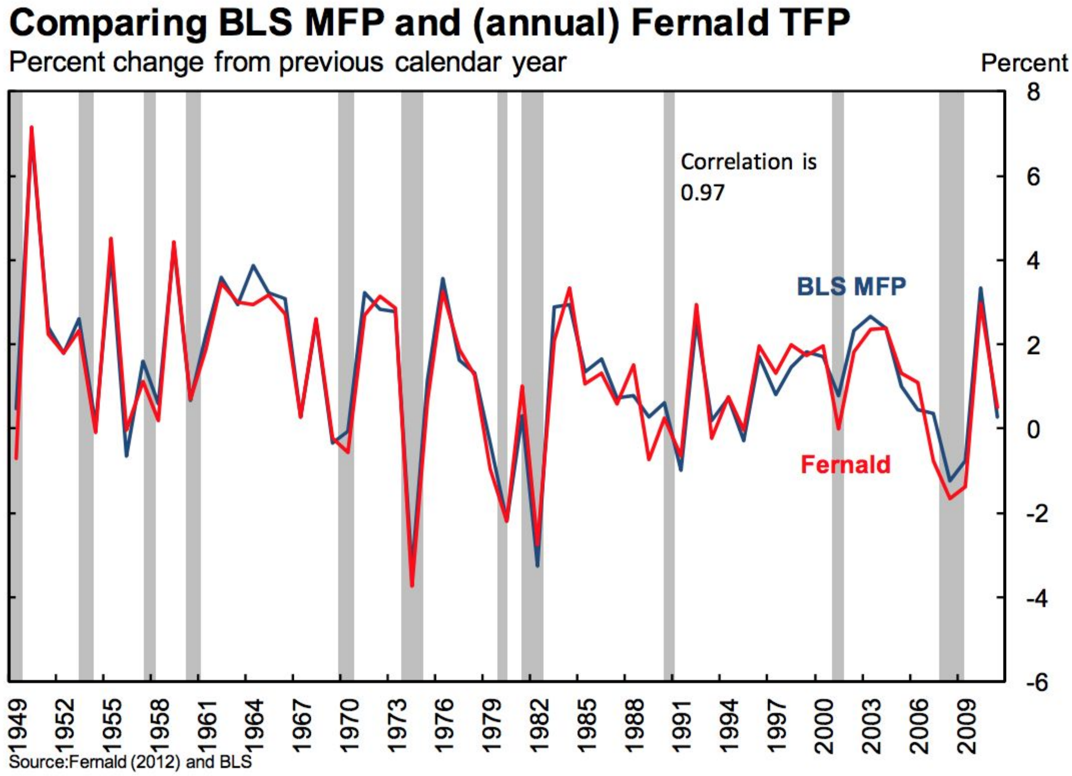
[14] On agricultural productivity comparisons, see Broadberry, Stephen, and Mary O'Mahony. "Britain's Twentieth-Century Productivity Performance in International Perspective." *Work and pay in the twentieth century* (2007): 301-329, and Broadberry, Stephen N., and Douglas A. Irwin. "Labor productivity in the United States and the United Kingdom during the nineteenth century." *Explorations in Economic History* 43, no. 2 (2006): 257-279.

[15] Fernald, John. "A quarterly, utilization-adjusted series on total factor productivity." Federal Reserve Bank of San Francisco, 2014.

Bureau of Labor Statistics, and one based on a cyclically-adjusted measure of capital utilization, from John Fernald at the Federal Reserve Bank of San Francisco.



If we restrict ourselves to the output-based, narrowly economic measures, TFP growth probably is the best contender for how to measure scientific progress. And overall TFP measures do show declines in the rate of innovativeness, expressed as a percentage of GDP. If you would find the above graph difficult to parse, and would like to see that described in words, here is an excerpt from Cowen's *The Complacent Class*: "During the period from 1919 to 1948, TFP [growth] averaged well over 2 percent a year, meaning that new ideas were contributing economic value at that rate, and in some particular years, TFP [growth] came in at over 3 percent. That represents the arrival of new ideas at a relatively high rate. Later, from 1948 to 1973, this measure of innovation still tended to average about 2 percent. But in 1973, TFP declined dramatically, often coming in below 1 percentage point a year, and for the most part, TFP stayed low until 1995, with an average of about 0.5 percent. The mid-1990s to early 2000s were a new golden age for TFP, which again at times ran at 2 percent or more…TFP slowed down, however, and in the most recent years, since the financial crisis, TFP has averaged well below 1 percent growth a year, only slightly above its disappointing 1973 to 1995 range. As productivity researchers John Fernald and Bing Wang put it: "Three out of the last four decades have seen business-sector productivity growth near 1.5%."[16]

Problems and ambiguities with TFP

[16] Cowen, Tyler, *The Complacent Class: The Self-Defeating Quest for the American Dream*. St. Martin's 2017.

Still, there are some reasons why TFP is far from a perfect measure of scientific progress.

For instance, all attempts to measure scientific progress through productivity come up against a timing problem: the innovation does not happen at the same time as it is adopted. When communication was more expensive, technologies spread more slowly. But even now, advances take time to diffuse and filter through into adoption—it may be many decades before they have been fully absorbed into society's productive apparatus.[17] Productivity series are still measuring technological progress, but they are measuring it with a long and variable lag and thus they may not track the progress of science very well. In the modern world, this is not always hugely telling: so many innovations are being developed and implemented at any one time that we do not tend to see much lumpy variation in the data of interest. Productivity tends to rise steadily. But at times of slower and less steady progress the gaps and the bursts can be more profound. In general, this militates against an overly literal interpretation of any data on productivity and what it means for how science is faring. The output gains of 2018 may be from what was learned in 2004 or in some cases even from 1983.

Consider the general numbers on lags in technology adoption, for instance as portrayed here:

As we see above in the chart, it can be decades before an invention becomes adopted by most households, although as we can see with recent technologies like the smartphone, tablet, and HDTV, the rate appears to be speeding up: while it took fifty years for 90% of US homes to have a stove cooker, it took only six for 90% to own a smartphone. That definitely represents a form of progress, though it does not in GDP statistics appear to outweigh the effects of other processes slowing down.

[17] Comin, Diego, Bart Hobijn, and Emilie Rovito. *Five facts you need to know about technology diffusion*. No. w11928. National Bureau of Economic Research, 2006.

Some of the additional problems with TFP are more conceptual.

First, many scientific advances work through enabling a greater supply of labor, capital, and land, and those advances will be undervalued by a TFP metric. Let's say someone invents a useful painkiller, and that makes it easier for many people to show up to work and be productive. Output will rise, yet that advance will show up as an increase in labor supply, rather than as an increase in technology or scientific knowledge. Similarly, a new method for discovering oil may boost output, but that will be classified as an increase in oil supply, even though it does properly represent a form of scientific progress. TFP is best at measuring scientific and technological advances that are superimposed on top of an existing supply of the other factors of production. If, for instance, you imagine a series of capital and labor resources at a factory, and someone develops a new formula for combining those resources more effectively, this will be picked up very effectively by standard TFP measures.

The more general problem is that many scientific and technological advances are embodied in concrete capital goods. Again, the TFP measure does best when the supply and nature of capital is fixed, and a new idea makes that capital (and associated labor) more effective. But what happens when the new idea is itself embodied in a concrete capital good? If a hospital equips its surgeons with iPads, or with Augmented Reality glasses, to make them more effective in the operating room, as a first order effect that measures as an increase of capital expenditures by the hospitals rather than as an innovation. Health and later output will increase, but will we really know if it is due to better ideas or just more investment? It will appear to measure as new investment. Capital expenditures and TFP are not so easily separated, whether at the conceptual or the practical measurement level.

Similarly, separating TFP from labor expenditure is not always so simple either. If a worker generates and carries forward a new scientific idea for producing more with a given amount of labor, that measures the same way as the worker being taught greater conscientiousness and producing more. Yet the former is (ideally) TFP and the latter is not, but both will count as an increase in the quality of labor input in the same way.

In defense of TFP measures, these problems are not always so serious *if these biases are roughly constant over time*. In that case, *changes* in TFP still would reflect *changes* in the rate of progress of science and technology. The absolute level of TFP could be biased by capital-embodied and labor-embodied technical change, but over time, for comparisons, the expected sign of that bias might be close to zero. Still, it is not obvious that the rate embodiment of new ideas into capital and labor, in percentage terms, should be constant over time. For instance, most societies are investing more in education, and capital is typically evolving from tangible to intangible forms; in both cases ideas could be embodied in capital and labour. Those major changes could be causing "new ideas" to be increasingly embodied in measurements of labor and capital over time, and that could mean we are undervaluing actual productivity gains. Nonetheless, this counter would be more persuasive if multi-year moving averages of GDP growth were constant (different accounting sources for a given amount of growth), but they are not, showing systematic decline. And it seems likely at least some of that decline is due to slowing productivity growth.

Another problem with TFP, already discussed in more general form above, is that the concept does not always deal clearly with advances in economic or institutional or organizational efficiency, and furthermore this represents some underlying ambiguities in the TFP concept.

To consider a simple example, imagine that an American company is inefficient, and then a management consultant comes along and teaches that company better personnel management practices, thereby boosting productivity. Does this count as an improvement in TFP or not? Or is it simply an increase in labor supply, namely that of the consultant? On one hand, some hitherto-neglected idea is introduced into the production process. That might militate in favor of counting it as TFP. On the other hand, the introduced idea is not a new one, and arguably the business firm in question is simply engaged in "catch up" economic growth, relative to more technologically sophisticated firms.

If we consult the very narrowest model of TFP, that model typically assumes that a series of perfectly competitive firms are already at the knowledge frontier, and thus there is a well-defined distinction between what is a gain in TFP or not. In other words, that model does not fully clarify the situation. The ways things actually proceed is that as TFP is measured empirically, the advances described in the above paragraph *would* count as TFP. yet conceptually those cases do not correspond exactly to what TFP is supposed to be about, namely new ideas, and thus from economists you will hear conflicting answers as to what TFP "really is."

The waters can be muddied further yet. Let's say that same consultant, before offering the advice to the inefficient business, first conducted some randomized controlled experiments on other companies, applied quality statistics to the results, ran an article through peer review, and then, based on that experimentation, offered the same advice. The whole process now look more like traditional science, but of course the advice and the final outcome are exactly the same. Would we then describe this change as a boost in TFP? If we are trying to assign logical categories to what counts as increases in factor supplies or ideas, it would seem that no change in classification is in order. If we are trying to apply common sense judgments to the actual process of developing the idea, it suddenly looks more like science and thus a boost in TFP.

We are not suggesting there are correct answers in principle to these classificatory dilemmas. In any case, they do seem to point out some ambiguities in the TFP concept, namely that there isn't always a simple matter of fact answer as to which applications of knowledge count as being "on the frontier" or not. If we define the frontier tautologically in terms of the status quo ex ante, it would seem that any application of knowledge, even copycat knowledge, counts as an increase in TFP. Alternatively, if we are using some other standard of what is knowledge at the frontier as opposed to catch-up knowledge, that distinction has not yet been outlined in sufficient detail and furthermore it will have a big impact on what gets measured as a TFP gain or not. The TFP standard becomes more fragile to the extent it depends on what appear to be fairly arbitrary distinctions.

Do TFP and related measures undervalue the contributions of the tech sector?

Some observers have argued there is significant under-measured progress in the tech sector, and that is another route for trying to argue the contemporary world is more progressive than TFP statistics alone might indicate. Yet there is suggestive evidence that the latest round of innovations in communications technology: smartphones, the internet, and so on, have not made as much of an impact as some intuitions may suggest. The hypothesis is that many recent innovations are increasing consumer welfare, but not by attracting consumer spending to specific goods and services. Thus, in this view, GDP is becoming an increasingly unreliable measure of output, let alone of welfare. For example, it is possible to have fun on Facebook or Wikipedia or Google, but without paying any upfront charge.[18]

Subsequent research has since indicated that these unmeasured gains are actually not so large, but first let's think through conceptually why that is the case. First and most importantly, the internet is increasingly commercialized. Being online makes it easier and often more efficient for us to spend money, for instance on Amazon.com, and those gains most definitely are picked up in measured GDP.

Second, most internet users do pay for their internet access through buying smartphones, iPads, cable connections, and other charges. Those expenditures most definitely show up in GDP. Subsequent use of the "free internet" is like taking the offerings at a buffet: you don't pay for every piece of chicken you grab, but you do pay an overall price for the buffet. Of course, to the extent the free internet is wonderful, more consumers will buy iPads, cable connections, and so on, again registering in GDP. The fact that we are charged for access to the free internet, in most cases, registers the economic value of those services. Of course there is consumer surplus from these services, but that is the case for all goods and services in the marketplace, including of course penicillin and other advances from earlier times. There is no clear evidence that internet use brings a higher consumer surplus than other innovations of the past, many of which were life-transforming. Furthermore, there is evidence that the income elasticity of demand for internet access is strongly positive, which would indicate the internet is not seen as a basic necessity.[19]

Third, we shouldn't expect mismeasured GDP simply from the fact that the internet makes many goods and services cheaper. Spotify provides access to a huge range of music, and very cheaply, such that consumers can listen in a year to albums that would have cost them tens of thousands of dollars in the CD or vinyl eras. Yet this won't lead to mismeasured GDP. For one thing, the gdp deflator already tries to capture these effects. But even if those efforts are imperfect, consider the broader economic interrelations. To the extent consumers save money on music, they have more to spend or invest elsewhere, and those alternative choices will indeed be captured by GDP. Another alternative (which does not seem to hold for music) is that the lower prices will increase the total amount of money spent on recorded music, which would mean a boost in recorded GDP for the music sector alone. Yet another alternative, more plausible, is that many artists give away their music on Spotify and YouTube to boost the demand for their live performances, and the increase in GDP shows up there. No matter how you slice the cake, cheaper goods and services should not in general lower measured GDP in a way that will generate significant mismeasurement.

Moving to the more formal studies, the Federal Reserve's David Byrne, with Fed & IMF colleagues, finds a productivity adjustment worth only a few basis points when attempting to account for the gains from cheaper

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[18] On issues related to the reliability of Real GDP growth figures, see Coyle, Diane. "All to play for in measuring the economy." (2017): 122-125, and Feldstein, Martin. "Underestimating the real growth of GDP, personal income, and productivity." *Journal of Economic Perspectives* 31, no. 2 (2017): 145-64, as well as Brynjolfsson, Erik, Felix Eggers, and Avinash Gannamaneni. "Using massive online choice experiments to measure changes in well-being." In *5th IMF Statistical Forum*. 2017. On accounting for the role of the internet in economic growth, see Hulten, Charles, and Leonard Nakamura. *Accounting for Growth in the Age of the Internet: The Importance of Output-Saving Technical Change*. No. w23315. National Bureau of Economic Research, 2017.

[19] On income elasticity, see Goel, Rajeev K., et.al. "Demand elasticities for internet services." *Applied Economics*, 39, 9: 975-980.

internet age and internet-enabled products. Work by Erik Brynjolfsson and Joo Hee Oh studies the allocation of time, and finds that people are valuing free Internet services at about $106 billion a year. That's well under one percent of GDP, and it is not nearly large enough to close the measured productivity gap. A study by Nakamura, Samuels, and Soloveichik measures the value of free media on the internet, and concludes it is a small fraction of GDP, for instance 0.005% of measured nominal GDP growth between 1998 and 2012.[20]

Economist Chad Syverson probably has done the most to deflate the idea of major unmeasured productivity gains through internet technologies. For instance, countries with much smaller tech sectors than the United States usually have had comparably sized productivity slowdowns. That suggests the problem is quite general, and not belied by unmeasured productivity gains. Furthermore, and perhaps more importantly, the productivity slowdown is quite large in scale, compared to the size of the tech sector. Using a conservative estimate, the productivity slowdown implies a cumulative loss of $2.7 trillion in GDP since the end of 2004; in other words, output would have been that much higher had the earlier rate of productivity growth been maintained. If unmeasured gains are to make up for that difference, that would have to be very large. For instance, consumer surplus would have to be five times higher in IT-related sectors than elsewhere in the economy, which seems implausibly large.[21]

Similarly, the tech sector of the American economy still isn't as big as many people think. The productivity gap has meant that measured GDP is about fifteen percent lower than it would have been under earlier rates of productivity growth. But if you look say about the tech sector in 2004, it is only about 7.7 percent of GDP (since the productivity slowdown is ongoing, picking a more recent and larger number is not actually appropriate here). A mismeasurement of that tech sector just doesn't seem nearly large enough to fill in for the productivity gap. You might argue in response that "today the whole economy is incorporating tech," but that doesn't seem to work either. For one thing, recent tech incorporations typically involve goods and services that are counted in GDP. Furthermore, there is a problem of timing, namely that the U.S. productivity slowdown dates back to 1973, and that is perhaps the single biggest problem for trying to attribute this gap mainly to under-measured innovations in the tech sector.

Other research looks at "worst case" scenarios from the mismeasurement of welfare adjustments in consumer price deflators and finds a similar result: a significant effect that nonetheless does not reverse the judgement that innovation has been slowing.[22]

The most general point of relevance here is simply that price deflator bias has been with productivity statistics since the beginning, and if anything the ability of those numbers to adjust for quality improvements may have

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[20] Byrne, David M., John G. Fernald, and Marshall B. Reinsdorf. "Does the United States have a productivity slowdown or a measurement problem?." *Brookings Papers on Economic Activity* 2016, no. 1 (2016): 109-182. And see Brynjolfsson and Joo Hee Oh, "The Attention Economy: Measuring the Value of Free Digital Services on the Internet." Completed research paper, 2012. On free media, see Nakamura, Leonard, Jon Samuels, and Rachel Soloveichik, "Valuing "Free" Media in GDP: An Experimental Approach," Working Paper 16-24, Federal Reserve Bank of Philadelphia, August 5, 2016.
[21] See Chad Syverson, "Challenges to Mismeasurement Explanations for the U.S. Productivity Slowdown." National Bureau of Economic Research Working Paper, 21974, February 2016.
[22] On slowing rates of innovation, see Reinsdorf, Marshall, and Paul Schreyer. "Measuring Consumer Inflation in a Digital Economy", as well as Bergeaud, Antonin, Gilbert Cette, and Remy Lecat. "Total factor productivity in advanced countries: A long-term perspective." *International Productivity Monitor* 32 (2017): 6.

increased with time. For instance, the research papers do not find that the mismeasurement has *risen* in the relevant period. You might think the introduction of the internet is still undervalued in measured GDP, but arguably the introduction of penicillin earlier in the 20th century was undervalued further yet. The market prices for those doses of penicillin probably did not reflect the value of the very large number of lives saved. So when we are comparing whether rates of progress have slowed down over time, and if we wish to salvage the performance of more recent times, we still need an argument that quality mismeasurement has *increased* over time. So far that case has not been made, and if you believe that the general science of statistics has made some advances, the opposite is more likely to be true, namely that mismeasurement biases are narrowing to some extent.[23]

II. DIRECT MEASURES OF SCIENTIFIC PROGRESS, OR THE SCIENCE OF SCIENCE

Many metrics of scientific advance show strong absolute progress over time. For instance, the annual growth rate of scientists is now over 4 percent, compared to a world annual population increase of about 1.1 percent. That means the number of researchers is doubling about every sixteen years, though note the most rapid growth often is coming in countries which are not on the scientific frontier. Still, in North America scientists are growing at a rate of 1.6 percent a year, alongside 1.5 percent growth in the EU, and growth of 1.9 percent in Japan.[24]

When it comes to the number of papers written, or the quantity of scientific work produced, there has been a veritable onslaught of effort. According to one well-known analysis, science is increasing in quantity by about eight to nine percent a year, or in other words it is doubling in size about every nine years. This is an estimate of citations not only of scientific papers but also of books, datasets and websites. Furthermore, that rate of increase has itself been increasing over time. The researchers write: "We identified three growth phases in the development of science, which each led to growth rates tripling in comparison with the previous phase: from less than 1% up to the middle of the 18th century, to 2 to 3% up to the period between the two world wars and 8 to 9% to 2012."[25]

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[23] On mismeasurement of GDP in undervaluing innovation, see Aghion, Philippe, Antonin Bergeaud, Timo Boppart, Peter J. Klenow, and Huiyu Li. *Missing growth from creative destruction*. No. w24023. National Bureau of Economic Research, 2017, as well as Charbonneau, Karyne, Alexa Evans, Subrata Sarker, and Lena Suchanek. *Digitalization and Inflation: A Review of the Literature*. Bank of Canada, 2017, and Bridgman, Benjamin. *Is productivity on vacation? The impact of the digital economy on the value of leisure*. mimeo, Bureau of Economic Analysis, 2016. Among the writers who still suggest that internet mismeasurement is a significant source of bias in GDP numbers are Hal Varian, Martin Feldstein, and Nick Crafts.

[24] See Baumberg, Jeremy J. The Secret Life of Science: How It Really Works and Why It Really Matters. Princeton: Princeton University Press, 2018, p.22.

[25] See Bornmann, Lutz and Ruediger Mutz, "Growth rates of modern science: A bibliometric analysis based on the number of publications and cited references," Journal of the Association for Information Science and technology, 2015, 29 April 2015, https://onlinelibrary.wiley.com/doi/full/10.1002/asi.23329. For a survey of this literature, see van Noorden, Richard "Global scientific output doubles every nine years," Nature News Blog, http://blogs.nature.com/news/2014/05/global-scientific-output-doubles-every-nine-years.html, accessed October 18, 2018. For a critique of bibliometric measures, see Anthony F.J. Raan, "Fatal attraction: conceptual and methodological problems in the ranking of universities by bibliometric methods." Scientometrics, 2005, 62, 1: 133-143.

To be sure, we don't regard such estimates as very precise, if only because it is arbitrary at the margins what counts as a citing scientific paper, or whether all citations should count for the same. Nonetheless we fully accept the conclusion that scientific inputs are being produced at a high and increasing rate, and this is the consensus of the literature too.

It is a mistake, however, to infer that increases in these inputs are necessarily good news for progress in science. As already mentioned, higher inputs are not valuable *per se*, but instead they are a measure of cost, namely how much is being invested in scientific activity. The higher the inputs, or the steeper the advance in investment, presumably we might expect to see progress in science be all the more impressive. If not, then perhaps we should be worried all the more. High and rising inputs are fully consistent with the hypothesis that progress in science is slowing down in critical regards.

Still, we can in fact learn about the nature of scientific progress by studying inputs, especially in those cases where we are able, however imperfectly, to measure quality. With that in mind let's consider some particular metrics for inputs related to progress in science, starting with patents.

Patents

Societies have invented institutions to codify inventions as original, new, and significant, with the introduction of patents in Venice in 1474. In principle, simply tracking patents is a good way of measuring the level of innovation in a society. Patents are only awarded when examiners have worked out whether the new idea is genuinely new and of sufficient importance, theoretically doing a lot of work for any later chronicler of scientific progress. And, although they were extremely spottily implemented around the world until the 19th century, they are now widespread and awarded under broadly similar terms across developed countries. What's more, in triadic patents (those registered in all of Japan, Europe and the USA) we have an automatic mechanism for pruning out errors, corruption, low quality trivial new ideas, and home-country bias. Patents, due to their complex application requirements, also give us detailed data on who, where and when ideas come from, which sector or industry they augment, and, in systems like the U.S. where citing existing patents is common, which ideas influence others.

Here is one simple look at how the number of patents has changed over time[26]:

[26] See Nagaoka, Sadao, Kazuyuki Motohashi, and Akira Goto. "Patent Statistics as an Economic Indicator." Chapter 25 in Handbook of Economic Innovation, Volume 2, 2010, 1083-1127.

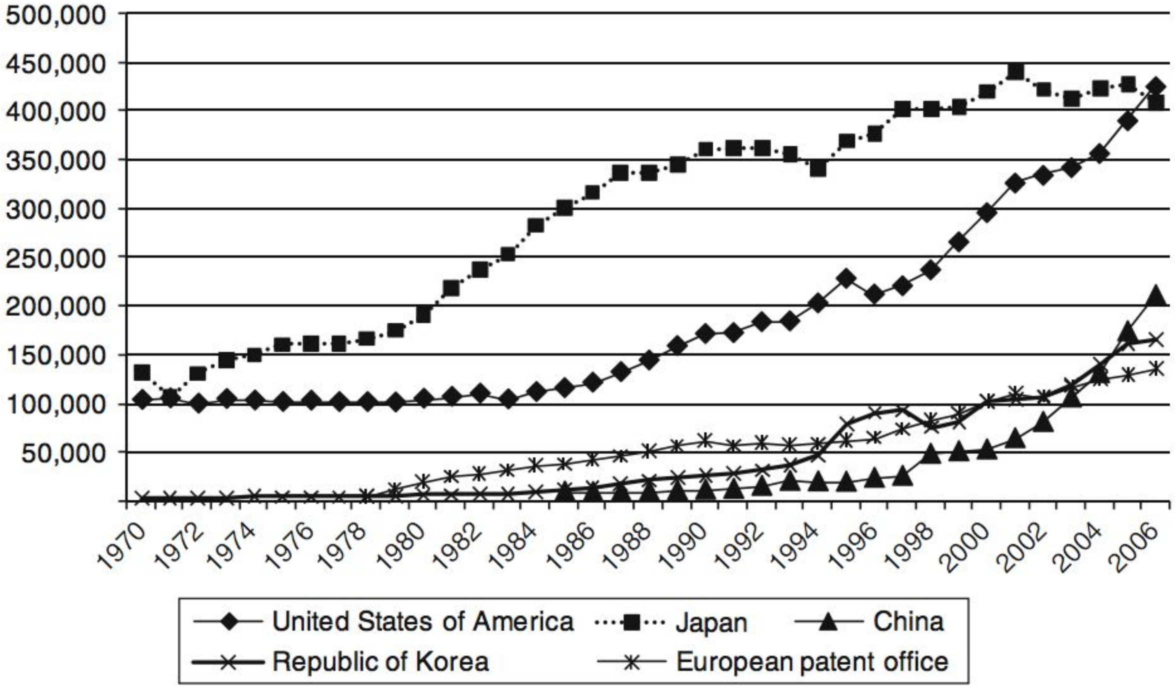

Figure 1. Patent applications at offices around the world (1).

(from Nagaoka et al)

Obviously that picture looks fairly positive, but if we adjust for patent quality the picture is murkier. Some recent research develops standards for "breakthrough" patents, namely those which fall in the top five percent of the quality distribution for patents overall. Breakthrough patents are measured by looking at citations but also by text-based measures, from the patent filing. Those text-based measures look for language which is both distinct from other patent filings, and also predictive of *future* citations for the patent. In this constructed series, patent quality is at a local peak in the 1990s and then declining. Patent quality is also *much* higher in the 1850s and 1860s than any time since. In general, breakthrough patents plunge fairly steeply in the 1990s. Note that this index is significantly related to future TFP growth, "with a one-standard deviation increase in our index associated with a 2 to 3 percent increase in future productivity." It thus should not be surprising that this metric is also showing some declines in the rate of progress.[27]

Another measure of patent quality is citations. Yet there is evidence that there has been a recent flood of low information citations in patents, and furthermore citation practices differ significantly across countries, so this measure is hard to use with much accuracy.[28] Another measure of the value of patents stems from the price

[27] See Kelly, Bryan, Dimitris Papanikolaou, Amit Sru,and Matt Taddy (2018) "Measuring Technological Innovation Over the Long Run," National Bureau of Economic Research Working Paper, in particular pp.26, 46, 50.

[28] On the rise of information-poor citations in the patenting process, see Kuhn, Jeffrey M, Kenneth A. Younge, and Alan Marco, (July 2017) "Patent Citations and Economic Analysis," working paper. For some cases where the number of patents does seem to correlate with actual scientific progress, see Webb, Michael, Nick Short, Nicholas Bloom, and Josh Lerner, "Some Facts of High-Tech Patenting," National Bureau of Economic Research Working Paper 24793, July 2018.

system, namely the value of the patent itself, or how patents might be reflected in values for the intangible capital of firms. Yet one problem with patent value measures is that value to owners does not coincide with value to society more broadly. For instance, a patent can represent a lucrative grant of monopoly privilege, connected with high prices and high profits, and the associated benefit to consumers might be relatively small. In any case values in this context are especially hard to measure as a trend through time.[29]

Note that some of the flaws with the patent metric also are consistent with the view that something has gone wrong in science. In particular, some of the increase in the number of patents is due to the greater ability and incentive to patent, rather than to scientific progress itself. We don't know how much the patent numbers are distorted by these factors, and so this seems to be an inconclusive metric.

Other metrics for intellectual production

Another measure of scientific progress is to look more generally at other numbers for intellectual production, again noting these will be highly imperfect measures and should be viewed in conjunction with other pieces of information. Nonetheless, innovators, books, crop yields, chip speed, and life expectancy are measurable in a relatively objective manner.[30]

Isaac Asimov, biochemist, science fiction author and polymath, took a direct but highly subjective approach in his *Biographical Encyclopaedia of Science and Technology*, listing 1,510 great scientists based mostly on his appraisal of their importance. A 1993 study by Bruce Gary charts these over time, finding a similar accelerating rise in citations in the industrial era, although less so when denominated by total population, when in fact the rate starts to decline in more recent eras. That again points us to an optimistic view on the totals but some pessimism in terms of how the per capita rates are changing.[31]

For a good, more general look at when patents do or do not predict subsequent innovation well, see Igami, Mitsuru and Jai Subrahmanyam, "Patent Statistics as an Innovation Indicator? Evidence from the Hard Disk Drive Industry," unpublished working paper, 2015. On cross-country differences in patent strength, see Cohen, W. M., Nelson, R. R., & Walsh, J. P. (2000). *Protecting their intellectual assets: Appropriability conditions and why US manufacturing firms patent (or not)* (No. w7552). National Bureau of Economic Research.

[29] On market value, see Hall, Bronwyn H., Grid Thoma, and Salvatore Torrisi. *The market value of patents and R&D: Evidence from European firms*. No. w13426. National Bureau of Economic Research, 2007, and also Hall, Bronwyn H., Adam Jaffe, and Manuel Trajtenberg (Spring 2005), "Market Value and Patent Citations," Rand Journal of Economics, 36, 1, 16-38. See also Antonipillai, Justin, and M. K. Lee. "Intellectual property and the US economy: 2016 update." *Washington, DC, Economics & Statistics Administration and US Patent and Trademark Office* (2016), and Nordhaus, William D. (2004). Schumpeterian profits in the American economy: Theory and measurement (No. w10433). National Bureau of Economic Research.

[30] See Howes (2016) for more.

[31] On appraisal of the relative importance of scientists, see Isaac Asimov, "En: Asimov's biographical encyclopedia of science and technology. The lives and achievement of 1510 great scientifics from ancient times to the present chronologically arranged. rev." (1982): 155-6. On per capita rates of innovation, see Gary, Bruce. L. (1993). "A New timescale for placing human events, derivation of per capita rate of innovation, and a speculation on the time of the demise of humanity." Note that his horizontal axis reflects a rather unusual treatment of time. The end of the graph is 1993, and so at that point 100% of the number of 1993 individuals are living on earth. The bump on the horizontal axis at 28% corresponds to the period 590 to 290 BC, as over that interval there was 28% of the later 1993 population. The minimum of the series of 38% corresponds to 390 to 500 AD, the so-called "Dark Ages." In essence this scale is trying to adjust for the varying number of individuals alive at any point in time; for more on that scale see Gary, Bruce *Genetic Enslavement: A*

Drawing upon Bruce Gary, consider this graph measuring the per capita innovation rate over time:

Call to Arms for Individual Liberation, Reductionist Publishing, 2011, chapter 29. On the production of new ideas, see Charles A. Murray, in his book *Human Accomplishment*, looks at the amount of space allotted to figures in the arts and sciences by encyclopedias and reference works to judge their significance. Murray's approach suffers from mostly filtering out all but the very top contributors (by design, it should be noted) but it nevertheless tells a similar story to the data from sources with wider coverage: disproportionate progress in certain regions and after the 1700s and the Industrial Revolution. It also finds evidence for a Lotka Curve effect, where intellectual impact follows an inverse square law: the most influential thinkers have far more impact than the next most influential, and so on. This suggests that capturing only the absolute top of the set will indeed proxy for the broader distribution of achievement. This is important also for wider data sources, because even the widest cannot hope to capture the full set of unrecorded tinkerers and tweakers through the distribution. For more detail, see Murray, Charles A. *Human Accomplishment: The pursuit of excellence in the arts and sciences, 800 BC to 1950*. Harper Collins, 2003.

You will note, however, that this graph shows a declining rate of innovation per capita, and not a decline in the absolute number of innovations enjoyed around the world. The total benefits of innovation seem to be high and rising, as discussed above in the productivity section, again returning to this common theme.

The two databases from Anton Howes and from Ralf Meisenzahl and Joel Mokyr, shown and cited below, consider hundreds of inventors from a short period, and not just the major and most famous figures. That said, they focus more narrowly on British innovators during the Industrial Revolution. They attempt to catalogue a much wider range of innovative activity, including the tweaks and modest implementations that allowed smaller ideas to translate into practical improvements. Nevertheless, their broad contours are the same as we see elsewhere: rapidly accelerating innovation in the 17th and 18th centuries, driven by more people, more population density, and more intellectual exchange.

Bunch and Hellemans compile a series of 8,583 important advances in science and technology across time. Jonathan Huebner takes the 7,198 of these that occurred between the Dark Ages and writing his paper in 2005, in order to chart their progress over time. This index correlates with Asimov's index of innovators with a coefficient of 0.85.[32]

[32] See Bunch, Bryan H., and Alexander Hellemans. *The history of science and technology: a browser's guide to the great discoveries, inventions, and the people who made them, from the dawn of time to today*. Houghton Mifflin Harcourt, 2004. On scientific advances since the Dark Ages, see Huebner, Jonathan. "A possible declining trend for worldwide innovation." *Technological Forecasting and Social Change* 72, no. 8 (2005): 980-986. Woodley, Michael A. "The social and scientific temporal correlates of genotypic intelligence and the Flynn effect." *Intelligence* 40, no. 2 (2012): 189-204. On correlation with Asimov's index, see Woodley, Michael A. "The social and scientific temporal correlates of genotypic intelligence and the Flynn effect." *Intelligence* 40, no. 2 (2012): 189-204.

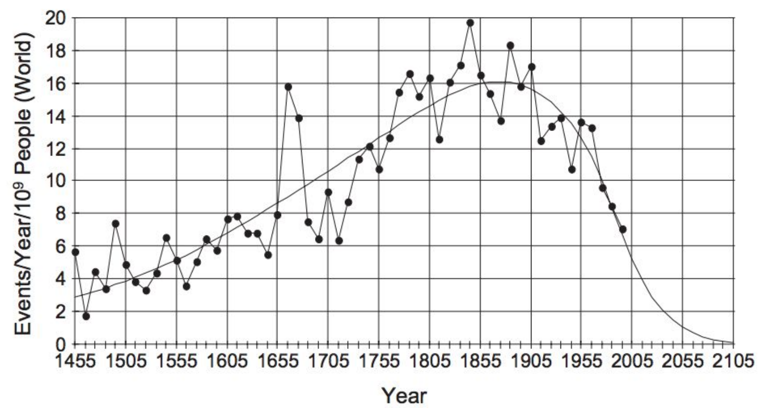

Fig. 1. Rate of innovation since the end of the Dark Ages. Points are an average over 10 years with the last point covering the period from 1990 to 1999. The smooth curve is a least squares fit of a modified Gaussian distribution to the data.

Again, Huebner's approach looks at the rate of innovation per capita, and not in total. His view is that technological progress is getting more difficult, or declining. The peak decade is the 1960s in their data, with a slowing and decline in positive rates since then. But an alternative interpretation is that prior to the mid 19th century, with its development of communication, literacy, and higher education institutions, civilization was not developing at its full underlying potential. That enabled a high rate of innovation per capita, since there was a lot of low-hanging fruit. Since then, we have hit or are pushing against various limits, whatever they may be. Our massive population increase should not be used to increase an ill-specified denominator, thereby making scientific progress appear less impressive, because in reality that progress is reaching a much greater number of people than ever before. Undenominated by population, scientific progress shows what is mostly a very positive story: a massive and rapid increase over time, accelerating with the industrial revolution.[33]

Several other papers judge that new ideas are indeed harder to find. Most prominently, four well-known economists -- Nicholas Bloom, Charles I. Jones, John Van Reenen and Michael Webb -- have written a paper "Are Ideas Getting Harder to Find?" Basically their answer is yes. They focus on measuring how many researchers are required, over time, to produce a significant breakthrough in scientific ideas. They find for instance that "…the number of researchers required to double chip density today is more than 18 times larger than the number required in the early 1970s." In this case of semiconductors, they conclude that research productivity is falling at about 6.8% a year. They find also that researchers have a declining productivity when it comes to crop yields, and also the mortality improvements associated with cancer and heart disease. We consider these topics separately below, but their core result is that increasing numbers of researchers are required to

[33] Huebner, Jonathan. "Discussion of Coates' commentary." *Technological Forecasting and Social Change* 73, no. 7 (2006): 906-912.

generate a given amount of percentage improvement in various areas, for instance as mentioned chip speed, crop yields, or mortality improvements.[34]

This paper is perhaps the strongest single piece of evidence on behalf of the claim that scientific progress is slowing down. At the macro level, the paper even finds the startling result that "research productivity for the aggregate U.S. economy has declined by a factor of 41 since the 1930s, an average decrease of more than 5% per year." This again follows from matching the growing number of researchers against other metrics of progress. In essence it means that per researcher productivity, by their measures, is being cut in half about every 13 years.

While we do accept the core conclusions of this paper, we also see it as too pessimistic about the course of scientific progress. The other metrics we have considered, while often supporting a pessimistic take on rates of change across per capita variables, do not seem to suggest a productivity deterioration comparable to what is found by Bloom, Jones, Van Reenen and Webb. So what might account for their extremely pessimistic take on per researcher productivity? After all, we do not see wages for researchers going down as their predictions for per researcher productivity might seem to predict.

A few factors may be relevant here. First, researchers may be working more to please themselves, or possibly to advance science in the abstract, rather than making useful applied science. In addition, many measured researchers may increasingly not be doing full-time research, but rather they are engaged in various bureaucratic enterprises specific to the modern university, or teaching. That bureaucratization is itself a sign (and also partial cause) of a productivity slowdown, but still it is distinct from the claim that *research* is becoming less productive to such an extreme degree. We are not measuring the actual number of true researchers very well, and so we may be over-measuring the decline in the productivity of research.

Second, science may not be a public good as much as in times past, so implementing new scientific ideas requires more scientific labor to fit those ideas to particular applied and commercial contexts (this point in particular helps explain why science as a whole is less productive but wages for scientists have not fallen).

Third, scientists work for non-scientists to implement their visions, and some of the productivity declines may be coming on the side of the non-scientists. The rates of productivity growth for American business have indeed declined over time, as discussed earlier in this paper. In response to that more general decline, we are indeed throwing more and more researchers (narrowly defined) at these problems. It thus appears that researcher productivity is declining dramatically, but in reality the measurement of "many more researchers per idea" may be in part a response to a prior but also more modest decline in general productivity, coming in part from the non-researcher side.

Fourth, the real gains in research may be concentrated in very new areas where the research productivity trends cannot be measured at all over time. For instance, "research in how to operate a social network" has boomed in the last fifteen years, but we cannot compare it to any numbers from the 1960s. The very fact of comparison over time may be selecting for the lower-productivity endeavors. Still, the fact that aggregate productivity

[34] See Bloom, Nicholas, Charles I. Jones, John Van Reenen and Michael Webb, "Are Ideas Getting Harder to Find?" Working paper, March 5, 2018, Version 2.0.

growth and aggregate gdp growth is trending downwards suggests that these dynamic new areas are not offsetting the stagnation in the old areas.

We are not sure of the relative import of those differing factors, but the aggregate slowdown in researcher productivity, while likely real, may be less than has been measured by Bloom, et.al.

If you still doubt the basic result from Bloom, et.al., there is secondary circumstantial evidence pointing in the same direction of their belief in a research productivity slowdown. For instance, the age at first innovation seems to be increasing in the US, as the stock of existing knowledge grows and it takes longer to absorb it before getting to the frontier. Doctorates are taking longer to complete, co-authorship is increasing, inventors are taking out fewer patents per capita, and research teams are growing larger. Scientists cite more papers in their research, and they take longer to get their first peer-reviewed publication. There seems to be a possible decline in the quality of Nobel prizes – fewer are for fundamental breakthroughs – in at least some scientific fields, such as physics, chemistry, and medicine. Finally, there are fewer "renaissance" men and women making impacts on several fields. It seems also that large scientific teams are less likely to make disruptive breakthroughs than are small teams. All of those factors are consistent with per person or per researcher innovation becoming harder and the notion that science and indeed society more generally is undergoing a steady bureaucratization.[35]

In disciplines such as Physics, Chemistry, and Physiology/Medicine, the average length of time between breakthrough and a subsequent Nobel Prize has increased from fifteen years to twenty-five years. This may reflect any number of changes, but is consistent with the view that the later breakthroughs are less obvious, less earth-shattering, and require a longer "test of time" for their merits to be apparent. Again, that supports the other indicators suggesting a slowdown in the rate of scientific progress.[36]

You will note that the evidence from these quarters, while not countermanding the notion of General Purpose Technologies, suggests that additional problems lie behind the science slowdown. It seems that science has become too bureaucratic, with too many inputs and too much process required to reach a given level of success. And this is indeed distinct from a slowing down of the import of General Purpose Technologies. That kind of slowdown implies that successive advances are less important on the user or consumer side, such as the notion that moving to safer cars is not as important as switching from horses and buggies to cars. The bureaucratization of the process, however, is a separate phenomenon and that bureaucratization implies there might be changes internal to the research process which could speed up scientific progress, perhaps considerably.

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[35] On the difficulty of finding new ideas, see Jones, Benjamin F. "The burden of knowledge and the "death of the renaissance man": Is innovation getting harder?." *The Review of Economic Studies* 76, no. 1 (2009): 283-317. On metrics showing the slowing of innovation, see Agrawal, Ajay, Avi Goldfarb, and Florenta Teodoridis. "Understanding the changing structure of scientific inquiry." *American Economic Journal: Applied Economics* 8, no. 1 (2016): 100-128, and Brendel, Jan, and Sascha Schweitzer. "The Burden of Knowledge in Economics." (2017). On large vs. small teams, see Wu, Lingfei, Dashun Wang, and James A. Evans, "Large teams develop and small teams disrupt science and technology," Nature, 13 February 2019. On the possible decline in quality in Nobel breakthroughs in many fields, see Collison and Nielsen, op.cit.
On the decline of "Renaissance" men and women, see Verhoeven, Dennis. "Potluck or Chef de Cuisine? Knowledge Diversity and Award-Winning Inventor Teams." SSRN working paper (2016).
[36] See Baumberg, Jeremy J. The Secret Life of Science: How It Really Works And Why It Matters. Princeton: Princeton University Press, 2018, p.46.

Now let's consider some other particular areas where data (and not explicit productivity statistics, as used in economics) might help us judge the quality of ongoing innovation.

Crop yields

Unlike many of the more economic variables we have considered, crop yields have the useful feature of being defined in physical rather than value terms. Corn, rice, and wheat, for instance, are to some extent physically constant over time, or their quality varies in fairly well-defined ways that can be measured. So rather than calculating TFP for an entire national economy, we can look at productivity gains in a few of the easier to measure areas. Agriculture is not in every way a representative sector, but its productivity gains do depend on materials technology, weather forecasting, information technology, vehicles and machines, and other areas where technologies advance. So data from agriculture do give us some clues as to what is happening with progress in broader areas of science. On net, the data show big improvements in the total quantity of crops produced over the longer term, but recent rates of growth seem to be mildly disappointing.

We cannot go as far back with crop yields as we can with population, at least in terms of direct measurement. We can estimate from archaeology and seed genetics what yields might have been, but there have been few attempts to construct a direct series. For crop yields, good information mostly exists for those places we have records, such as England and Wales, although there is some data for other European countries, as well as Japan and China.[37]

As best we can tell, early progress was significant, though slow relative to modern rates. For instance, output per acre was around 3.2x higher in 1850 England than during the medieval period. In this period, it was apparently small innovations, mostly to do with nitrogen fixation, that boosted yields: those include the Norfolk "four course" rotation and the introduction of clover. Tenure arrangements, i.e. institutions, also changed over the period, with land enclosure in England leading to larger, more concentrated, and more productive farms.[38]

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[37] On global historical crop yields, see Broadberry, Stephen, and Bas van Leeuwen. "English agricultural output 1250–1450: some preliminary estimates." In *Third workshop for Working Group*, vol. 2, pp. 1-43. 2008. Aposolides, A., Stephen Broadberry, Bruce Campbell, Mark Overton, and Bas van Leeuwen. "English agricultural output and labour productivity, 1250-1850: some preliminary estimates." (2008). Allen, Robert C. "English and Welsh agriculture, 1300-1850: outputs, inputs, and income." (2005). Allen, Robert C. "Economic structure and agricultural productivity in Europe, 1300–1800." *European Review of Economic History* 4, no. 1 (2000): 1-25. Bassino, J. P., S. Broadberry, K. Fukao, B. Gupta, and M. Takashima. *Japan and the great divergence, 730–1872. University of Warwick: Centre for Competitive Advantage in the Global Economy*. No. 230. Working Paper Series, 2015.
[38] On historical rates of output in England, see Clark, Gregory. "The agricultural revolution and the industrial revolution: England, 1500-1912." *Unpublished manuscript, Department of Economics, University of California, Davis*(2002). On the role of nitrogen fixation in boosting crop yields, see Allen, Robert C. "The nitrogen hypothesis and the English agricultural revolution: A biological analysis." *The Journal of Economic History* 68, no. 1 (2008): 182-210. Note: A complication is that mortality also declined, life expectancy increased, and the interest rate declined: a competing hypothesis is that existing innovations were merely applied more due to a lower time preference and less myopia among farmers; see Nicolini, Esteban. "Adult mortality and investment: a new explanation of the English agricultural productivity in the 18th century." Universidad Carlos III de Madrid. Instituto Figuerola, 2001.

After 1800, although agriculture shrinks as a share of the economy, and as a share of employment and of land use, its total output continues growing. One recent series looks at 2.5m agricultural statistics for 13,500 political units around the world and finds that yields in major crops are still growing at around 1% per year over the past few decades. This growth is stronger in developed countries, where new innovations are applied more rapidly.[39]

That is good news, but still the overall picture crop yields in the last few decades is a complex one but partly pessimistic.

One study of maize, rice, wheat and soybeans finds that "...across 24-39% of maize-, rice-, wheat-, and soybean-growing areas, yields either never improve, stagnage or collapse." That is for the time period 1961-2008, and note that while yields are still increasing in most regions, those are steady rather than explosive or accelerating increases for the most part. And while this study surveys only a few crops, maize, rice, and wheat, taken alone, account for more than half of the world's calories. Related work shows that yields for those crops are increasing in the range of 0.9% to 1.6% a year, when by some estimates a 2.4% rate of growth will be needed to feed global population by 2050. Furthermore, there is good evidence for yield plateaus in many parts of the world, including for East Asian rice and wheat in northwest Europe.[40]

Bloom, et.al. in their study find that the per researcher contribution to crop yields is falling at the average annual rate of about 3.7 percent a year, a sign that the science in this area is yielding diminishing returns, at least for the time being. And they find specific results for corn, soybeans, wheat, and for one version of cotton, with the other cotton version showing (mild) improving researcher productivity over time. In their results, crop yields have been rising at about 1.5 percent a year for these four crops, and the number of researchers has been rising much faster than that (by more than a factor of 23 for both corn and soybeans), yet without yielding much in the way of improved results.[41]

Health and life expectancy

Another constant in human progress is health. We can look at various measures of health care, health outcomes, and overall lifespan to track progress in these areas.

Starting in earlier historical times, Neil Cummins looks at 115,650 European nobles who lived between 800 and 1800 AD, drawing heavily on the unparalleled family tree records kept by the Mormon Church of Jesus Christ

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[39] On the growth of crop yields, see Ray, Deepak K., Nathaniel D. Mueller, Paul C. West, and Jonathan A. Foley. "Yield trends are insufficient to double global crop production by 2050." *PloS one* 8, no. 6 (2013): e66428. On the role of innovation in boosting crop yields, see Fuglie, Keith O., and Sun Ling Wang. "New evidence points to robust but uneven productivity growth in global agriculture." *Amber Waves* 10, no. 3 (2012): 1.

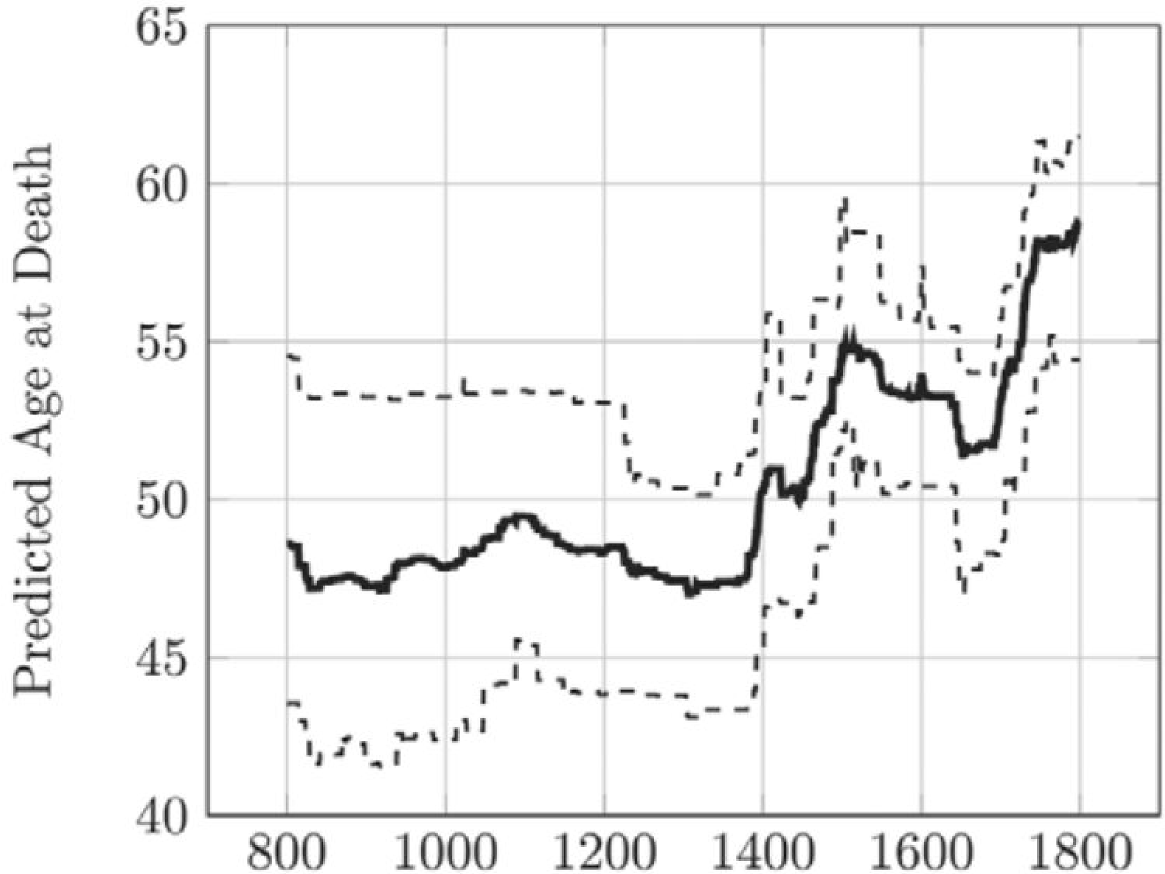
[40] See Ray, Deepak K., Navin Ramankutty, Nathaniel D. Mueller, Paul C. West, and Jonathan A. Foley, "Recent patterns of crop yield growth and stagnation." Nature Communications, 18 December 2012, DOI: 10.1038/ncomms2296. On the 2050 projection, see Ray, Deepak K., Nathaniel D. Mueller, Paul C. West, and Jonathan A. Foley, "Yield Trends are Insufficient to Double Global Crop Production by 2050." Plos One, June 2013, 8, 6: 1-8. On yield plateaus, see Grassini, Patricio, Kent M. Eskridge, and Kenneth G. Cassman, "Distinguishing between yield advances and yield plateaus in historical crop production trends." Nature Communications, 17 December 2013, DOI: 10.1038/ncomms3918.

[41] See Bloom, Nicholas, Charles I. Jones, John Van Reenen and Michael Webb, "Are Ideas Getting Harder to Find?" Working paper, March 5, 2018, Version 2.0.

of Latter-day Saints. Of course, trends for nobles will never accurately represent trends for the population at large; more nobles die in battle, and fewer die from famines or plagues. And as we have seen with all of our data sources, records are much more readily available for some countries (especially Northwest Europe, and within Northwest Europe, especially England and Wales). But they provide an interesting illustration of progress along one possible dimension, namely living longer.[42]

Overall the gains here are clear, as illustrated below:

[42] On European lifespans, see Cummins, Neil. "Lifespans of the European elite, 800–1800." *The Journal of Economic History* 77, no. 2 (2017): 406-439. Note: For recent moves, we can augment this by looking at Disability-Adjusted Life Years (DALYs) or Quality-Adjusted Life Years (QALYs), which are often calculated in ingenious ways to work out the value of various healthcare interventions. However, these will not extend far back enough, nor be applicable to enough countries now, to allow as many detailed comparisons as we would want. One problem with the life expectancy metric is that life expectancy occasionally goes down when technology improves and filters across society. For example, the spread of coal across the UK undoubtedly reflected scientific and technical advance, but it cut life expectancy significantly for affected localities. In general new polluting technologies will typically worsen health and lifespan and boost economic output. This may or may not be a worthwhile improvement, but either way it is certainly technological innovation, so life expectancy will sometimes mismeasure scientific progress from our perspective. Still, the broad contours of life expectancy do not seem heavily shifted by this problem.



(a) Sample Average

What we see is a flat trend for the medieval period, before some jumps in the renaissance and early modern eras. By 1800, noble life expectancy was nearly 60 years, which later in the 1940s the UK population as a whole attained (note that is high than for some UK neighborhoods now). And although nobles died frequently in wars (the top ten days for mortality in the sample are all the dates of famous battles), most of this decline in premature death was not from the reduced frequency and lethality of battles. Instead, it came from a slow but steady build-up of medical recommendations and general increases in public health.

David de la Croix and Omar Licandro find evidence of progress, though with a later starting point than in the work of Cummins. Their data look at a much wider sample of famous people from history. Considering around 300,000 people who lived between 2400 BC and 1879, they find no trend in life expectancy until the 1640s, when lifespans begin to increase. A quintet of Dutch authors find some similar results, as they attempt to zero in on the transmission mechanism (medical knowledge) by looking at the lifespans of medical professionals, who lacked the extreme wealth and social status of nobles. They did not have impressive life expectancies, consistent with the view that medical progress was not significant until some point in the twentieth century.[43]

We see also that it was not until the late 19th and early 20th centuries when public health improvements filtered through to the wider population. Suddenly a quite broad swathe of the population had clean water, access to doctors for basic services, and the infrastructural improvements that brought better hygiene.[44] This came first through improvements that reduced infant mortality, which affected richer countries in the first half of the 1900s, and then, from the mid 20th century, from improvements that extended the end of life.

If we consider rates of change for life expectancy in more recent times, however, the picture is somewhat less giddy. There we see steady improvement, but at a more or less constant pace in percentage terms. For instance, since 1950, life expectancy for Americans, defined as at birth, has risen at about 1.8 years per decade. Life expectancy at age 65 has increased roughly by 0.9 years for each decade. These are both standard results. However, in the first half of the twentieth century, American life expectancy rose at the much higher rate of 3.8 years per decade. Evidence from the United Kingdom also indicates that life expectancy has been increasing at a less rapid rate since the mid-1950s. Overall, that is pretty strong evidence for scientific progress slowing in that one particular area, and that is indeed an important area for anyone alive.[45]

For a visual look at comparable evidence from the United States, here is one look at the life expectancy trend since 1800[46]:

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[43] On life expectancy trends, see De la Croix, David, and Omar Licandro. "The longevity of famous people from Hammurabi to Einstein." *Journal of Economic Growth* 20, no. 3 (2015): 263-303. On the lifespans of medical professionals in the Netherlands, see Van Poppel, Frans, Govert Bijwaard, Mart Van Lieburg, Fred Van Lieburg, Rik Hoekstra, and Frans Verkade. "The Life Expectancy of Medical Professionals in the Netherlands, Sixteenth to Twentieth Centuries." *Population, English edition* 71, no. 4 (2016): 619-640.

[44] On public health improvements and life expectancy, see Cutler, David, and Grant Miller. "The role of public health improvements in health advances: the twentieth-century United States." *Demography* 42, no. 1 (2005): 1-22. Alsan, Marcella, and Claudia Goldin. *Watersheds in infant mortality: The role of effective water and sewerage infrastructure, 1880 to 1915*. No. w21263. National Bureau of Economic Research, 2015. Kesztenbaum, Lionel, and Jean-Laurent Rosenthal. "Sewers' diffusion and the decline of mortality: The case of Paris, 1880–1914." *Journal of Urban Economics* 98 (2017): 174-186. Birchenall, Javier A. "Economic development and the escape from high mortality." *World development* 35, no. 4 (2007): 543-568.

[45] On U.S. life expectancy, see Bloom, Nicholas, Charles I. Jones, John Van Reenen, and Michael Webb, "Are Ideas Getting Harder to Find?", March 5, 2018, Version 2.0. On the United Kingdom, see Adrian Gallop, "Mortality improvements and evolution of life expectancies," working paper, http://www.osfi-bsif.gc.ca/Eng/Docs/DEIP_Gallop.pdf, accessed 19 October 2018. For background, see Lee, Ronald D. and Lawrence R. Carter, "Modeling and Forecasting U.S. Mortality." Journal of the American Statistical Association, September 1992, 87, 419: 659-671

[46] See Catillon, Maryaline, David M. Cutler, and Thomas E. Getzen, "Two hundred years of health and medical care." VoxEU CEPR Policy Portal, 9 February 2019.

Unfortunately, in the last few years, a surprising number of U.S. counties have shown *decreasing* life expectancy, obviously a sign of partial retrogression. Furthermore, for 2015 and 2016 the nation as a whole exhibited *declining* life expectancy. While the causes of this change have not been pinpointed rigorously, it is generally believed to have something to do with substance abuse and the opioid epidemic and also a higher suicide rate. While those factors would not count as scientific retrogression, it likely reflects a decline in both social capital and institutional capacity in the American health care system in some manner. On net, it seems that scientific progress is not outracing institutional declines, and that too can be taken as a marker that scientific progress, in the life expectancy area, is not faring very impressively.[47]

Computer power and Moore's Law

Though it may seem like a recent human preoccupation, computational power is in fact an issue throughout most of human civilisation. Aides to human ability to process information have existed for thousands of years, at least since the apparent computational device found in an ancient Greek shipwreck, or the Babylonian Salamis Tablet (dated to 300 BC). The Romans used a hand-abacus that had grooves to move counters, and the

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[47] See "Health, United States," National Center for Health Statistics, Centers for Disease Control and Prevention, 2017, available on-line at https://www.cdc.gov/nchs/hus/description.htm, accessed October 10, 2018.

modern abacus dates from 1200s China. By the early-to-mid 1800s, inventors were creating simple and unwieldy mechanical computers that could perform arithmetic operations or follow simple programs.

William Nordhaus attempts to construct an index of overall computer power over time, in order to track the effects of new computing technologies over time.[48] Because he wants to capture all of the benefits, he doesn't just look at raw computing power of technologies, but also the cost of computing, to capture improvements that make technologies cheaper but not more effective per se. But both his series for raw computing power and computer power deflated by its cost tell us the same thing, namely that there was an incredible boost in computing power, starting in the 1930-1950 period, as can be seen in the above diagram. And of course that time period is special for a number of different measures of scientific progress, as discussed elsewhere in this paper.

[48] Nordhaus, William D. "Two centuries of productivity growth in computing." *The Journal of Economic History* 67, no. 1 (2007): 128-159.

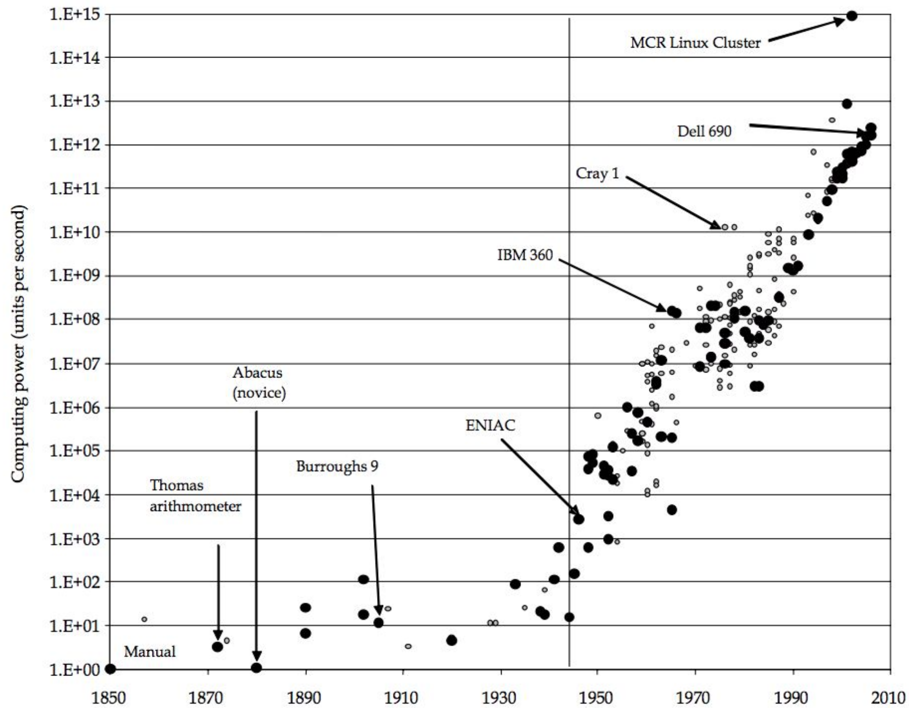

FIGURE 2
THE PROGRESS OF COMPUTING POWER MEASURED IN COMPUTATIONS PER SECOND (CPS)

Notes: The measure shown here is the index of computing power. For a discussion of the definition, see the text. The series is defined so that manual computing has a value of one. The large circles are estimates that have been judged relatively reliable, and the small circles are estimates in the literature that have not been independently verified. The vertical line is placed at 1944, which is the estimated breakpoint in productivity growth.
Source: As described in the text.

The next question, however, is whether computing power has continued to improve in power and cheapness in more recent times, and there the evidence suggests a slowing down of the gains. At its height, Moore's Law implies a 20 to 30 percent annual decline in the costs of manufacturing a transistor, to give one example. That has helped chip sizes shrink dramatically, leading first to the personal computer and later to the iPhone. But Moore's Law has slowed down, at least as measured by the prices for the products sold with the highest volumes, namely memory chips, outsourced custom chip designs, and Intel microprocessors. Moore's Law seemed to be accelerating in the 1990s, up through about 2010, as a three-year cycle for new technologies was replaced by a two-year cycle. But since 2014, comparable breakthroughs have not come along at the same pace, arguably with a four-year cycle replacing a two-year cycle. There have been other recent slowdowns, for instance around 2003-2004 higher clock rates stalled, and rapid cost decline seem to have gone away since about 2012. Many industry observers have suggested the radical conclusion that chips may stop getting smaller by about 2021. And if you wish to compare rates of price declines for memory chips, heterogeneity of product makes this a little difficult but still the 1974-2011 period shows rates of price decline in the general range of 17 to 45 percent, with one data point at a ten percent rate of price decline for one particular chip over a five-year period.

Price data for 2011-2016 show rates of price change ranging from +2.33 percent (an increase) through -13.57 percent, a much less impressive performance. Other indices also show slow downs in chip price deflation rates since about 2011.[49]

Consider the following diagram:

These numbers are sufficiently new that they should be interpreted with caution, and of course the trend of a slowdown still may be reversed, or a breakthrough such as quantum computing may change the basic equation entirely. Still, the exact same data used to illustrate Moore's Law now suggest that Moore's Law definitely is slowing down. And that is evidence for a scientific slowdown in what arguably has been the world's single most dynamic sector, namely information processing.

III. CONCLUDING REMARKS

To sum up the basic conclusions of this paper, there is good and also wide-ranging evidence that the rate of scientific progress has indeed slowed down, In the disparate and partially independent areas of productivity growth, total factor productivity, GDP growth, patent measures, researcher productivity, crop yields, life expectancy, and Moore's Law we have found support for this claim.

One implication here is we should not be especially optimistic about the productivity slowdown, as that notion is commonly understood, ending any time soon. There is some lag between scientific progress and practical outputs, and with science at less than its maximum dynamic state, one might not expect future productivity to

[49] See Flamm, Kenneth. "Measuring Moore's Law: Evidence from Price, Cost, and Quality Indexes." National Bureau of Economic Research Working Paper 24553, April 2018.

fare so well either. Under one more specific interpretation of the data, a new General Purpose Technology might be required to kickstart economic growth once again.

In our investigation, we saw some ambiguity in the notion of science. Typically, in the "science of science" literature, the notion of science would refer more narrowly to research conducted in universities and the private sector and government, and would not include purely organizational and institutional improvements in the broader polity. Yet from a logical point of view those improvements still would seem to represent scientific progress of some kind or another, even if they are a neglected kind for historians of science. Their incorporation into a broader understanding could help us salvage some of the status of science in the contemporary world. However you wish to label the phenomenon, the nation of China for instance really does work much better than it did in the relatively recent past, as is also the case for much of the world's population, especially in the emerging economies.

When we look at the numbers, the growth in aggregate magnitudes is far more encouraging. The world supports more people than before, a given innovation is enjoyed by more people than before, and aggregate wealth is on the rise. Overall, aggregate rates for global economic growth have been robust. Science is much bigger and better than in the past, no matter what may be the case with various per capita rate of change magnitudes. Progress on the aggregates but not the per capita rates of change seems to reflect quite significant and indeed somewhat neglected features of the contemporary world.

We might consider that the contemporary world may have two particular specialties. First, we may be living in a time where organizational and institutional improvements are easier to come by than gains in pure science, in the narrow sense of that term. Second, we may be living in a time where "building out the aggregates" is proceeding more effectively and more powerfully than "boosting the productivity of individual component parts."

One general lesson is that the concrete forms and manifestations of progress change over time, often radically. If we do not acknowledge this, we will end up as more pessimistic than we ought to be, just as we may for instance observe the decline of Baroque music but neglect the later rise of rock and roll and then rap music. That said, while the decline of Baroque music as a dominant form probably was inevitable, it hardly seems the case that traditional scientific research has to slow down in its rates of progress, at least not to the extent it has. In future work, we hope to turn to the question of how we might revitalize scientific progress, in the narrower sense, once again. Some of our magnitudes did seem to imply that current science has become excessively bureaucratic, and that is in principle a remediable problem.
However one somewhat pessimistic possibility, quite speculative, is that rising overall plenitude and declining marginal efficacy are part and parcel of the same broad set of processes. For instance, the major progress on per capita rates of change (but weaker performance on total magnitudes) may be easier to achieve when a relatively small number of countries enjoy a relatively protected position in the overall world order. Those days of course are now long since gone. Perhaps one understanding of progress, scientific and otherwise, can be had by describing some kind of broader model with dual features, some positive some negative, rather than insisting on a single judgment for whether progress is rising or falling.

Perhaps the next question is for how long "building out the aggregates" will last as the dominant successful mode of progress. A related question is whether altruists and philanthropists today should be focused on doubling down on what the contemporary world seems to be good at -- boosting totals -- or trying to reverse or moderate or balance that skill for purposes of diversification, as well as for remediation of lower rates of per capita improvement in the wealthier countries. A great deal hangs on this question, though we do not see it being framed as such very often.

In terms of general method, one response to the general question of progress would be to bicker over whether the proper mood, in response to all of these metrics and magnitudes, is optimism or pessimism. Yet arguing over moods is not always fruitful, as those debates cannot readily be reduced to factual questions. In any case, as was learned in the earlier 17th and 18th century debates about progress, a debate about progress is never a debate about progress alone.