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The Ultimate Resource is Peaking

Charles Kenny

Abstract

Julian Simon argued that more people were associated with more prosperity: human talents were the “ultimate resource” and the force behind rising living standards. The last 30 years have been consistent with that view. But, globally, we are making fewer workers—and, more importantly, fewer potential innovators. In rich countries, human capital is growing considerably more slowly than in the past. Meanwhile innovation per researcher appears to be dropping as the population of researchers ages, while it takes longer to get to the knowledge frontier and more collaboration to expand it. Combined with the fact we are increasingly intolerant of risk and increasingly desirous of innovations in sectors where it is particularly hard to increase productivity, it is little surprise that productivity growth is indeed declining. To extend our two-century era of comparatively rapid progress we need radically reduced discrimination in the global opportunity to innovate.

KEYWORDS
technology, demographics, economic growth

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The Ultimate Resource is Peaking

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Introduction

Against the Malthusian worldview in which population growth encroached on natural limits to output, condemning humanity to poverty, Julian Simon argued that more (educated) people were associated with more prosperity. Simon's 1981 book *The Ultimate Resource* suggested that human talents were the force behind rising living standards and, in particular, that talent-powered adaptation and innovation prevented natural resources becoming a constraint on progress.

Since then, work by Michael Kremer and others has pointed in a similar direction: the period of most rapid global per capita income growth has been that with the largest global populations.[1] And, as predicted by Simon, natural resources have remained sufficiently abundant that they have not constrained growth. Marian Tupy and Gale Pooley look at the prices of 50 commodities from bananas through iron, natural gas, wheat and wool over the period 1980 to 2018 and find that the amount of time the average person on planet earth would have to work in order to buy a basket of those commodities fell by 72 percent over that 38 year period.[2] "Human capital" rules in terms of global output: the World Bank estimates stocks of natural capital including farmland and subsoil assets accounted for just six percent of global capital stocks in 2018, compared to 64 percent for human capital (the remainder being produced capital: houses, factories, offices, infrastructure).[3]

But Simon was also worried that the human resource constraint appeared to be tightening. "There is only one important resource which has shown a trend of increasing scarcity rather than increasing abundance. That resource is the most important of all—human beings…. if we measure the scarcity of people the same way that we measure the scarcity of other economic goods—by how much we must pay to obtain their services—we see that wages and salaries have been going up all over the world … a clear indication that people are becoming more scarce even though there are more of us."[4]

This is, of course, mostly to be celebrated. Higher incomes are a vital part of improved quality of life. But a growing "ultimate resource scarcity" really is upon us. We continue to make progress in our ability to find, extract and efficiently use natural resources to create value. But we are making fewer workers—and, more importantly, fewer potential innovators. Evidence of declining productivity in research and development adds to these concerns. We can surely extend our two-century era of comparatively rapid progress through reduced discrimination and a greater focus on innovation, but it still appears likely that the rate of growth of living standards will eventually decline. On the plus side, a world of ten billion living sustainably at a technology frontier still slowly expanding would be beyond the most utopian dreams of our forebears: it is no reason to panic.

1 Kremer, M. (1993). Population growth and technological change: One million BC to 1990. *The Quarterly Journal of Economics*, *108*(3), 681–716.
2 Tupy, M. and Tooley, G. (2022). *Superabundance* Washington DC: Cato Institute.
3 World Bank. (2021). *The Changing Wealth of Nations 2021: Managing Assets for the Future*. Washington, DC: World Bank, Table 3.4.
4 Simon, J. L. (1994). More People, Greater Wealth, More Resources, Healthier Environment. *Economic Affairs*, 14: 22–29.

Imagine a simple model of progress.[5] Technology is the key to output—more technology equals more production. Technology growth is a function of population and education, but as technology becomes more advanced, the benefits of population decline relative to education and, as it advances further, a declining marginal return to education sets in. In turn, education growth is a function of stocks of technology, because exploiting the marginal technological advance requires an increasing level of education (and so increases the returns to that education). Population increases with output (and so technology) but rising output *per person* slows population growth, as does more education.

Going through those assumptions in turn, the idea that technology is the "lever of riches" (to quote Joel Mokyr) is widely accepted.[6] Far more than stocks of physical capital (infrastructure, factories) or (even) labor augmented by education, it is the fact that the amount produced by an equally educated worker operating with the same amount of capital stock has skyrocketed rather than declined with growing stocks which lies behind prosperity.[7]

What lies behind technology growth is people innovating—creating new ideas and products. With more people, there are more minds to innovate. That said, as technology accumulates, it is less likely that someone who cannot build on the knowledge of past innovators through learning will be able to create something on the technology frontier (the technological innovation of stirrup required an understanding of horsemanship alongside some understanding of leather and ironworking, the Covid-19 vaccine a PhD level understanding of RNA manipulation and much else besides). Over time, the amount of learning required to reach the frontier has increased beyond the ability of one person to accomplish it alone, so that innovation becomes ever more a transactions-heavy process of collaboration, reducing technology production per educated person.

5 This is a model that borrows heavily from Galor, O., & Weil, D. N. (2000). Population, technology, and growth: From Malthusian stagnation to the demographic transition and beyond. *American Economic Review*, *90*(4), 806–828. Note however that returns to education are associated with the level of technology not technology growth, income levels (not change) determine fertility, the model assumes a declining return from education and population to technology and that exploiting technology near the frontier takes an ever larger stock of human capital (Robert C. Allen, Technology and the great divergence: Global economic development since 1820, Explorations in Economic History, Volume 49, Issue 1, 2012, Pages 1–16 suggests this with regard to physical capital). Galor and Weil in turn build on the model of Michael Kremer, and, going further back, Auguste Comte argued in the early Nineteenth Century that the rate of progress was determined by levels of population (which increases pressure to innovate to stay above subsistence as well as allowing for division of labor), urbanization, life expectancy and boredom. Note Comte, like Simon, wasn't worried about Malthusian counter-forces because by the time land pressure was an issue, the global population would be tenfold what it was in his day and "the more complete development of human nature ... will no doubt supply new means of resistance to the danger." (see Van Doren, 1967 *The Idea of Progress* Praeger NY p. 45 & p. 364). For a related model that emphasizes population growth and institutions see Jones, C. I. (2001). Was an industrial revolution inevitable? Economic growth over the very long run. *The BE Journal of Macroeconomics*, *1*(2). I am (sort of) following Glaeser, E. L., La Porta, R., Lopez-de-Silanes, F., & Shleifer, A. (2004). Do institutions cause growth? *Journal of economic Growth*, *9*(3), 271–303 in assuming education is a primary underlying cause of better policies and institutions.

6 Mokyr, J. (1992). *The lever of riches: Technological creativity and economic progress*. Oxford University Press.

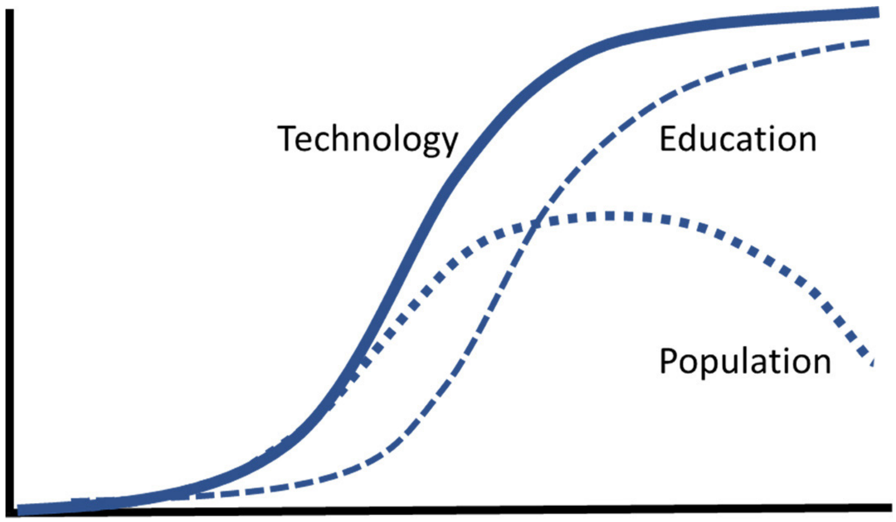
7 Easterly, W., & Levine, R. (2001). What have we learned from a decade of empirical research on growth? It's Not Factor Accumulation: Stylized Facts and Growth Models. *The World Bank Economic Review*, *15*(2), 177–219. Jones, C. I. (2016). The facts of economic growth. In *Handbook of macroeconomics* (Vol. 2, pp. 3–69). Elsevier. 23–49. (Although this is disputed; see: Baier, S. L., Dwyer Jr, G. P., & Tamura, R. (2006). How important are capital and total factor productivity for economic growth? *Economic Inquiry*, *44*(1)).

Education rises in value as technology advances: not only does innovation require more learning, but *utilizing* (at least producer) technology advance does as well: literacy to understand machine instructions and related management skills.[8] Turning to population growth, more output (including more food and medicines) allows for more people. But a greater opportunity cost of parental time due to rising incomes, declining mortality thanks to better nutrition and medication, and a rising value of education all shift the quantity-quality tradeoff with regard to children towards quality: fewer, more educated.

Start with a world of low population, very low education and limited technology—the pre-industrial world. At that point, technology advance is slow and what advance there is usually results in slightly more rapid population growth rather than sustained higher incomes. But the slow growth of population ensures technology advance slowly accelerates in turn, feeding back on population growth but also increasing returns to education. A more educated workforce speeds technological growth but also drives a wedge between rising output and population—and, as incomes rise, the wedge grows. At some point, however, declining returns to education set in: even a more educated population, certainly aging and potentially shrinking by that point, is inadequate to extend the run of rapid technological progress. As long as there are still people, technological progress does not stop, but it does considerably slow down (See Figure 1). In this paper I will argue that we are approaching the upper end of the technology and education s-curve, and near the peak of the population curve.

8 See for example Foster, A. D., & Rosenzweig, M. R. (1996). Technical change and human-capital returns and investments: evidence from the green revolution. *The American Economic Review*, 931–953, Doms, M., Dunne, T., & Troske, K. R. (1997). Workers, wages, and technology. *The Quarterly Journal of Economics*, *112*(1), 253–290. On the limited need for literacy at the start of the Industrial Revolution see: Mitch, D. (2016). *The rise of popular literacy in Victorian England: the influence of private choice and public policy*. University of Pennsylvania Press. Again, In the early decades of the Twentieth Century, as electrification spread across America, firms that had more equipment and got more of their power from electricity started hiring more educated workers, who they paid more Goldin, C., & Katz, L. F. (1998). The origins of technology-skill complementarity. *The Quarterly Journal of Economics, 113*(3), 693–732. Note skills premia did not apparently *rise* in Europe over the Nineteenth Century, but given the considerable expansion of education, that they did not fall is a sign of increased demand (Clark, G. (2005). The condition of the working class in England, 1209–2004. *Journal of Political Economy*, *113*(6), 1307–1340). Note that some technologies are specifically designed to reduce demand for skills (self-driving cars, self-checkout), but it does appear there does seem to be a close interaction between the rollout of new technology and increased demands for human capital).

FIGURE 1. Technology, population, and education over time?



Technology is at least to a considerable degree a global public good.[9] If it is the major force behind economic growth, what explains divergence of global incomes? In part it is that the education required to exploit technology is (also) a good imperfectly produced by the market. Direct consumers (children) are particularly ill-suited to judge quality or returns. But so, often, are parents, especially those with limited education themselves. In addition, education is a long-term investment in the next generation: credit constraints and uncertain returns especially at the start of the period of modern economic growth are likely to limit investment. Again, education has spillovers in that it is an important source of technology advance.[10] Along with concerns over nation building, these will be reasons why there was a strong elite push for public, universal education in industrializing countries in the Nineteenth Century.[11]

Note, however, that demand did not extend to universal education for colonial subjects: cost, racist beliefs around the supposed lower cognitive ability among indigenous populations, and a desire for colonies to focus on primary production surely all played a role.[12] Even colonial subjects who enjoyed the opportunity of schooling faced obstacles to advance, reducing the demand for available education.

9 In considerable part, but far from completely. The international intellectual property regime is a barrier to adoption alongside trade secrets. In addition, while not taking way from their public good nature, technologies are designed for a particular setting—institutional, cultural, environmental, economic—and their utility can be considerably lower in other settings.

10 Poterba, J. M. (1994). *Government Intervention in the Markets for Education and Health Care: How and Why?* (No. 4916). National Bureau of Economic Research.

11 See Galor, Oded. (2005). "Unified growth theory." *Handbook of Economic Growth,* 1: 171–293.

12 In Africa, for example, as late as the Second World War most schooling was provided by missionaries rather than the state. By 1950 estimated gross primary school enrollments (age 5–14) were below 10 percent for about one third of British and French colonies including Tanzania and Senegal and above 30 percent in only six colonies. Frankema, E. H. (2012). The origins of formal education in sub-Saharan Africa: was British rule more benign? *European Review of Economic History*, *16*(4), 335–355.

This favored concentration of both modern production as well as technological advance in richer countries, which subsequently created new productive technologies requiring ever higher levels of education to manipulate, severely limiting the impact of technological advance on production in developing countries where education stocks remained limited.[13] These countries nonetheless benefited from the resulting products themselves through trade: not least cheaper food and better medicine, which fostered population growth and convergence in measures of quality of life.[14] With independence and the spread of universal public education, the global education gap began to close, leading to the potential for dramatic rates of 'catch up' growth for economies able to combine education with the policy fundamentals involved with export competitiveness.[15]

Note this model misses important facets: not least, there is a large gap between the total (educated) population and the population with the opportunity and ability to innovate, and we will see that the technology we want has changed over time, from innovations that maximize material prosperity toward innovations which improve the quality of services. These factors may well considerably extend or reduce the period of rapid technological change. But the rest of this paper will argue we are nonetheless reaching toward the top of the technology s-curve.

The next sections provide evidence that population is peaking and that is linked to education and technology, but also that raw population becoming a less important driver of innovation. Education is plateauing in turn and returns to education in terms of technology advance seem to be declining. The paper elaborates on two reasons as to why suggested by the model: a growing distance to the frontier of knowledge and growing transactions costs related to the increased necessity of cooperation. It adds three more potential factors not directly implied by the model: aging, risk averseness, and that innovations we want are increasingly the innovations we are bad at producing. Next, the paper points to the fact that overall technology advance indeed appears to be slowing. The paper then turns to possible responses involving a better institutional environment to innovate, greater equality of opportunity in innovation and the potential role of artificial intelligence.

13 Acemoglu, D. (2003). Factor prices and technical change: from induced innovations to recent debates. *Knowledge, Information and Expectations in Modern Macroeconomics*, 464–491. Acemoglu, D. (2002). Directed technical change. *The Review of Economic Studies*, *69*(4), 781–809. Allen, R. C. (2012). Technology and the great divergence: Global economic development since 1820. *Explorations in Economic History*, *49*(1), 1–16.

14 Between 2000–2019, an estimated 37 million lives were saved by routine vaccination in developing countries, the vast majority of which were children. Li, X., Mukandavire, C., Cucunubá, Z. M., Londono, S. E., Abbas, K., Clapham, H. E. et al. (2021). Estimating the health impact of vaccination against ten pathogens in 98 low-income and middle-income countries from 2000 to 2030: a modelling study. *The Lancet*, *397*(10272), 398–408. About 23% of the food produced for human consumption is traded internationally, and the food trade is a major factor behind considerably reduced global famine deaths. D'odorico, P., Carr, J. A., Laio, F., Ridolfi, L., & Vandoni, S. (2014). Feeding humanity through global food trade. *Earth's Future*, *2*(9), 458–469. On famine deaths see: https://ourworldindata.org/famines#the-our-world-in-data-dataset-of-famines. On global quality of life see Kenny, C. (2005). Why are we worried about income? Nearly everything that matters is converging. *World Development*, *33*(1), 1–19.

15 Aizenman, J., & Spiegel, M. M. (2010). Takeoffs. *Review of Development Economics*, *14*(2), 177–196. Hausmann, R., Pritchett, L., & Rodrik, D. (2005). Growth accelerations. *Journal of Economic Growth*, *10*(4), 303–329.

A caveat on (fuzzy) definitions and a resulting weakness in this paper: technology in its broad sense is the application of knowledge for practical purposes. In this paper, it frequently shrinks to being shorthand for techniques and approaches which reverse the expected declining return to capital and labor allowing ever more (market) output for a given set of (market) inputs, reflected in total factor productivity measures. And often the measures of technology advance I use are even less reflective of its broader meaning, including patent counts. A lot of the ways that technology (writ large) has influenced wellbeing are ill-reflected in market statistics (let alone patent counts) and the picture might well look different if those influences were better reflected. This is a subject for further work.

Ultimate resource supply constraints

With regard to population, the evidence is particularly clear that we are heading toward a global peak. Two years before Simon wrote about scarce humanity, Gary Becker warned that: "The price of children is the net cost of rearing them, and obviously depends on the cost of food, clothing, and housing. [But it] also depends on the value of the time spent on child care by parents, typically mothers. The foregone value of the time spent rearing children in modern economies is well over half the total cost."[16] That, he suggested, was a powerful force behind declining birth rates. Since he wrote, the opportunity cost of child rearing has continued to rise worldwide thanks both to greater gender equality and rising overall incomes, and fertility has dropped dramatically.[17] Partly as a result, but also because returns to education combined with rapidly declining child mortality have led to a more acute quantity-quality tradeoff, we have passed peak child.[18] More children were born in 2012 than any previous year in history. But more children were born in 2012 than any year since then, too.[19]

Across the richer parts of the world, fertility rates have dropped below replacement levels. High income fertility rates fell from 1.8 to 1.6 births between 1990 and 2019, while average rates in upper-middle income countries fell from 2.5 to 1.8 over the same time. Increasing life expectancy has so far blunted the impact on overall population levels, but that also accounts for a growing number of retirees. By 2050, there will be one retirement age person for every two people of working age in

16 Becker, G. S. (1992). Fertility and the Economy. *Journal of Population Economics*, *5*(3), 185–201.

17 It is worth noting we have also significantly raised the direct cost of childhood for parents, through regulatory interventions from car seats through requirements that children under a certain age should not be unaccompanied. See Nickerson, Jordan and Solomon, David H., Car Seats as Contraception (July 31, 2020). Available at SSRN: https://ssrn.com/abstract=3665046 or http://dx.doi.org/10.2139/ssrn.3665046.

18 Chen, J., & Guo, J. (2022). The effect of female education on fertility: Evidence from China's compulsory schooling reform. *Economics of Education Review*, *88*, 102257. Schultz, T. P. (2001). *The Fertility Transition: Economic Explanations* (Yale University Economic Growth Center Discussion Paper No. 833). Murtin, F. (2013). "Long-term determinants of the demographic transition, 1870–2000." *Review of Economics and Statistics, 95*(2), 617–631 . Klemp, M. P., & Weisdorf, J. (2012). *Fecundity, Fertility and Family Reconstitution Data: The Child Quantity-Quality Trade-O Revisite* (No. 9121). CEPR Discussion Papers. Vargha, L., & Donehower, G. (2019). The quantity-quality tradeoff: A cross-country comparison of market and nonmarket investments per child in relation to fertility. *Population and Development Review*, 321–350. Liu, H., & Li, L. (2022). The quantity–quality fertility–education trade-off. *IZA World of Labor*, 143–143.

19 See https://ourworldindata.org/grapher/births-and-deaths-projected-to-2100, accessed 10/28/2022.

high-income countries compared to one for every five as recently as 1990. In countries including Italy, Japan and South Korea, there will be more old and young dependents combined than workers in 2050.[20]

The UN predicts peak working age population (20–64) for high income countries in 2023, at 740 million people. Add in upper middle income countries including Brazil and China and the peak comes just four years later, in 2027, at 2.31 billion people. By 2050, the high income working age population will have dropped to 682 million (an 8 percent decline from the peak in just 27 years). Add in upper middle income countries, and there will be 209 million fewer working age people in 2050 than at the 2027 peak, a decline of more than 9 percent in just 23 years.[21]

It is worth noting that the countries which are currently responsible for the considerable majority of global innovation include some of those that are also seeing the most rapidly shrinking populations. As an imperfect measure, in 2020, China, the US, Japan, the Republic of Korea and Germany between them accounted for 93 percent of resident patent applications worldwide.[22] UN predictions suggest that, collectively, their population aged 20 to 64 will be 184 million smaller in 2050 than it was in 2020.[23] China's working age population will drop by 160 million people between now and 2050—that *change* is about equal to the current *total* working age populations of Germany, the UK and Japan combined.

While poorer developing countries are further behind, they are also transitioning to low fertility and old age far more rapidly than did wealthier countries in the past. Bangladesh already has a fertility rate below replacement levels, and India's at 2.2 children per woman, is barely above it.[24] The world as a whole will reach peak working age population in the 2070s or before.

One direct response to this challenge would be to try to raise birth rates. Countries have tried various approaches including Singapore's 'National Night,' complete with a song: "I'm a patriotic husband you're my patriotic wife, let's do our civic duty and manufacture life." Not content, the country also introduced 'baby bonuses'—about $1,500 for the second child and twice that for the third—alongside child tax credits.[25] Singapore's fertility rate is currently 1.14 per woman—only marginally above half of the replacement rate.[26] The Czech Republic doubled birth allowances and its parental leave benefit

20 Kenny, C. (2021). Global Mobility: Confronting A World Workforce Imbalance. CGD Note.

21 Author's calculation from 2022 UN population projections, medium variant, accessed 7/19/22 https://population.un.org/wpp/Download/Standard/Population/.

22 World Bank World Development Indicators Patent applications, residents (IP.PAT.RESD) accessed 7/1/2022.

23 Kenny, C. (2021). Confronting a World Workforce Imbalance CGD Note.

24 World Bank World Development Indicators https://data.worldbank.org/indicator/SP.DYN.TFRT.IN accessed 10/28/2022.

25 Jones, G. W., & Hamid, W. (2015). Singapore's pro-natalist policies: To what extent have they worked? In *Low and lower fertility* (pp. 33–61). Springer, Cham.

26 World Bank World Development Indicators https://data.worldbank.org/indicator/SP.DYN.TFRT.IN?locations=SG accessed 10/28/2022.

in 2007—four years later, the country's birth rate was unchanged.[27] Across countries, evidence suggests payments to parents do have some effect on birth rates, but it is small.[28] Government-provided or subsidized childcare in Norway, Italy and Spain have also worked to increase fertility (as well as women's labor force participation), but fertility rates in those countries remain at 1.2 (Italy, Spain) to 1.5 (Norway) births per woman.[29]

The role of education

Simon noted the role of education in the knowledge production function, and including it does extend grounds for optimism.[30] Raw population appears to be an ever-worse measure of innovative capacity, with the size of the educated population mattering far more. Using the imperfect measure of patenting once again, over time, more Swedish inventors who patent have a PhD.[31] In Japan and the US, 88 percent and 94 percent respectively of international patent holders have a college degree and 13 percent and 45 percent have a PhD.[32] Looking across countries at variation in resident patenting, and accounting for the size of the *tertiary-educated* population over 25, the *total* population over 25 is actually slightly *negatively* associated with patenting levels.[33]

The good news is that America and the World as a whole has never been more educated, giving even more people the opportunity to stand on the shoulders of giants by learning about innovations and discoveries of the past. In 1950, there were only 28 million people of working age (20–65) worldwide who had post-secondary education. By 2020, that had risen to 840 million people, and the number

27 Goldstein, J. R., Sobotka, T., & Jasilioniene, A. (2009). The end of "lowest-low" fertility? *Population and Development Review*, *35*(4), 663–699.

28 Gauthier, A. H., & Hatzius, J. (1997). Family benefits and fertility: An econometric analysis. *Population Studies*, *51*(3), 295–306.

29 Baizán, P. (2009). Regional child care availability and fertility decisions in Spain. *Demographic Research*, *21*, 803–842. Rindfuss, R. R., Guilkey, D. K., Morgan, S. P., & Kravdal, Ø. (2010). Child-care availability and fertility in Norway. *Population and Development Review*, *36*(4), 725–748. Del Boca, D. (2002). The effect of child care and part time opportunities on participation and fertility decisions in Italy. *Journal of Population Economics*, *15*(3), 549–573. World Bank World Development Indicators https://data.worldbank.org/indicator/SP.DYN.TFRT.IN accessed 10/28/2022. Limiting or at least compensating for regulatory changes that raise the cost of child care can also help. Nickerson, J., & Solomon, D. H. (2020). Car seats as contraception. *Available at SSRN 3665046*.

30 Simon, J. L., & Boggs, R. (1997). Trends in the quantities of education: A pictorial essay. *Economics of Education Review*, *16*(1), 69–80.

31 Jung, T., & Ejermo, O. (2014). Demographic patterns and trends in patenting: Gender, age, and education of inventors. *Technological Forecasting and Social Change*, *86*, 110–124.

32 Walsh, J. P., & Nagaoka, S. (2009). Who invents? Evidence from the Japan-US inventor survey. *RIETI Discussion papers*, *24*. See also Varsakelis, N. C. (2006). Education, political institutions and innovative activity: A cross-country empirical investigation. *Research Policy*, *35*(7), 1083–1090. Ding, H. (2006). The determinants of Innovation: An Empirical cross-country study of 43 countries for 1998–2002. *Applied Econometrics and International Development*, *6*(1).

33 Data from World Bank World Development Indicators, https://databank.worldbank.org/source/world-development-indicators, accessed 10/28/2022, 49 countries with 2015 tertiary education stock (SE.TER.CUAT.ST.ZS) and patent data (IP.PAT.RESD). Population over 25 estimated as (SP.POP.TOTL*((100-(SP.POP.1519.MA.5Y+ SP.POP.2024.MA.5Y))/100)-SP.POP.0014.TO).

may climb past a billion by 2030.[34] In the US, the proportion of 18–24 year olds who are in college or who have completed at least some college has risen from 38 percent in 1967 to 63 percent in 2020.[35] In China, the gross tertiary enrollment rate (the number of college students expressed as a proportion of the college age population) was only about one in a thousand in 1970, now it is closer to six out of ten. In Germany, the rate climbed from 34 percent in 1991 to 73 percent in 2019, in South Korea from 38 to 98 percent over that same period. College enrollments worldwide have climbed from 10 percent to 40 percent over the past half-century.[36]

But educational attainment is not rising as fast as it was. Barro and Lee provide measures of average years of education in the population above fifteen and the size of that population. The stock of education was rising at an annualized rate of 2.7 percent in the US between 1950 and 1980 and at 1.4 percent in the years between 1980 and 2010. For China the same numbers are 6.0 percent for the earlier period and 3.1 percent for the later period (although notably, for Germany, there was an acceleration, from 0.8 percent to 2.3 percent).[37] In the US since the 1990s, education rates have levelled: roughly 85% of kids graduate from high school, roughly one third graduate from 4-year colleges.[38] US undergraduate enrollment actually fell from 18.1 million in 2010 to 15.9 million in 2020 and the number of PhDs awarded has plateaued.[39] Stocks of human capital per person in the country that include a measure of working hours climbed by about 60 percent between 1960 and 2000, but there it has stuck thanks both to stalling enrollment and a declining proportion of working age people in the population who are working somewhat fewer hours.[40] Looking forward, worldwide, the working age (20–65) population with post-secondary education doubled between 2000 and 2020, but it may only increase 58 percent 2020–2040.[41]

With regard to the quality of that education, sadly, we have failed to find innovation that allows for rapidly improved learning speeds. Indeed, according to available measures we spend more and more

34 Data from Wittgenstein Center http://dataexplorer.wittgensteincentre.org/wcde-v2/ Lutz, W., Goujon, A., K.C., S., Stonawski, M., & Stilianakis, N. (2018). Demographic and Human Capital Scenarios for the 21st Century: 2018 assessment for 201 countries. Publications Office of the European Union, Luxembourg.

35 Data from US Census: https://www.census.gov/data/tables/time-series/demo/school-enrollment/cps-historical-time-series.html accessed 10/28/2022.

36 Data from World Bank World Bank World Development Indicators https://data.worldbank.org/indicator/SE.TER.ENRR accessed 10/28/2022.

37 Author's calculation from the Barro-Lee dataset available here: http://www.barrolee.com/ accessed 10/28/2022.

38 Jones, C. I. (2022). The past and future of economic growth: A semi-endogenous perspective. *Annual Review of Economics*, *14*, 125–152.

39 Data from NCES https://nces.ed.gov/programs/coe/indicator/cha https://ncses.nsf.gov/pubs/nsf22300/report/u-s-doctorate-awards accessed 10/28/2022.

40 Vollrath, D. (2020). *Fully Grown: Why a Stagnant Economy is a Sign of Success*. University of Chicago Press. P. 32.

41 Data from Wittgenstein Center http://dataexplorer.wittgensteincentre.org/wcde-v2/ Lutz, W., Goujon, A., K.C., S., Stonawski, M., & Stilianakis, N. (2018). Demographic and Human Capital Scenarios for the 21st Century: 2018 assessment for 201 countries. Publications Office of the European Union, Luxembourg.

on education while test scores are flat and PhD completion takes ever longer.[42] In the second half of the Twentieth Century, US spending on education increased sixfold on a real per capita basis,[43] while the evidence on improving test scores over that period is at best mildly positive.[44] Meanwhile, the decline in the frequency of Nobel-worthy achievements among younger scientists is not primarily driven by a declining youth population but reflects a sharp decline in early life productivity. In part that is because even future Nobel prize winners have been taking longer to finish their PhD studies, and that rising age of graduation tracks the rising age of Nobel-worthy research.[45]

Declining returns?

More immediately concerning, there appears to be a declining return in terms of technology development from each educated person. Put another way, the amount of research effort required to sustain the same rate of technology growth is rising. For example, Bloom, Jones, Van Reenen, and Webb estimate that the number of researchers working on semiconductors has increased eighteenfold since 1971, but Moore's law (the doubling of chip density every two years) applied throughout that period. That suggests recently it has required 18 times the amount of research effort as in the early 1970s in order to double chip density. Looking at agricultural yields, there are 25 times the crop researchers in the US compared to 1960, but corn yields have only increased linearly.[46]

Models that link researcher numbers with output often implicitly assume that researchers create knowledge that instantly diffuses economy wide and leads to a permanent increase in output. That's an important over-simplification: most technology diffusion models suggest there can be decades between a new innovation and its ubiquitous adoption. In addition, technologies do eventually become obsolete. And if you look at some specific examples—measures of wheat yields and research effort behind new wheat varieties in the US, for example—using these more complex models,

42 In the US, standardized test scores at 17 are within the margin of error of their level in the early 1970s (Data from NCES https://nces.ed.gov/programs/digest/d21/tables/dt21_221.85.asp accessed 10/28/2022), college graduation rates appear to be increasing because of grade inflation rather than greater learning (Denning, Jeffrey T., Eric R. Eide, Kevin J. Mumford, Richard W. Patterson, and Merrill Warnick. (2022). "Why Have College Completion Rates Increased?" *American Economic Journal: Applied Economics*, 14 (3), 1–29.) and PhD completion times from entry into graduate school are actually down from heights in the mid 1990s, but they have still climbed from 6.7 to 7.5 years 1970–2020. Data from National Science Foundation https://ncses.nsf.gov/pubs/nsf22300/data-tables Table 31 accessed 10/28/2022. See also Brendel, J., & Schweitzer, S. (2019). The burden of knowledge in mathematics. *Open Economics*, *2*(1), 139–149 on the growing age of first authorship (alongside collaboration) in mathematics journal and Schweitzer, S., & Brendel, J. (2021). A burden of knowledge creation in academic research: evidence from publication data. *Industry and Innovation*, *28*(3), 283–306 on the same trends in economics.

43 Huebner, J. (2005). A possible declining trend for worldwide innovation. *Technological Forecasting and Social Change*, *72*(8), 980–986

44 Shakeel, M., & Peterson, P. E. (2022). A Half Century of Progress in US Student Achievement: Agency and Flynn Effects, Ethnic and SES Differences. *Educational Psychology Review*, 1–88.

45 Jones, B., Reedy, E. J., & Weinberg, B. A. (2014). Age and scientific genius (No. w19866). National Bureau of Economic Research.

46 Bloom, N., Jones, C. I., Van Reenen, J., & Webb, M. (2020). Are ideas getting harder to find? *American Economic Review*, *110*(4), 1104–44.

you don't see evidence of declining researcher productivity.[47] But those more complex models taken to their limits are perhaps even more, and surely excessively, depressing: it suggests a constant level of research effort would at some point be fully taken up with replacing obsolete technologies, potentially implying zero effect on output growth.

Again, if you account for the fact that researchers produce their breakthroughs in increasingly fancy labs filled with expensive equipment, the picture might be a little brighter: Jakub Growiec and colleagues suggest that allowing for their measure of R&D capital, labor productivity of researchers as measured in numbers of patents produced has actually been climbing at about one percent a year.[48] The bad news is that raw patent counts are a weak measure of technological advance. Measures of patent quality (likelihood of being cited and so on) suggest that it has been declining.[49] The overall number of patents issued has been skyrocketing at a time when measures of output and total factor productivity growth have been heading in the other direction. And the role of physical capital is decidedly secondary as a persistent factor in the creation of scientific knowledge.[50]

Finally, it is worth caveating that just because trends in a particular line of enquiry show decreasing returns (understanding the nature of the universe, fitting more transistors on the chip, maximizing wheat yields) does not damn enquiry in the aggregate to similar decline. Instead, we can switch to another line of enquiry: The major solution to global food shortages was not perfecting bird poop mining on the Guano Islands, but switching to the Haber-Bosch process to create artificial fertilizer. Or we can find utterly new products or services to perfect in a new way (as it might be online bookselling or lithium-ion battery weight for storage). Even if Moore's law itself is breaking down, Christopher McGee and colleagues suggest exponential progress can be seen in the cost of optical fiber capacity, lumens of light produced by a dollar's worth of LEDs, the watt-hours produced by a kilogram of battery weight, and in areas from electricity transmission through superconductivity to engines and turbines and genome sequencing. Protein folding, mRNA, geothermal power and the cost of space launches dropping two hundredfold suggest exponential isn't dead yet, even if it has switched gear.[51]

47 Alston, J. M., & Pardey, P. G. (2022). Are Ideas Really Getting Harder to Find? (University of Minnesota Department of Economics Staff Paper No. 1701-2022-787).

48 Growiec, J., McAdam, P., & Mućk, J. (2022). Are Ideas Really Getting Harder To Find? R&D Capital and the Idea Production Function (Warsaw School of Economics Working Paper No. 2022–071).

49 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.

50 See for example Bombs, Brains, and Science: The Role of Human and Physical Capital for the Creation of Scientific Knowledge Fabian Waldinger, *The Review of Economics and Statistics* (2016) *98*(5), 811–831. He compares the impact of the dismissal of scientists in Nazi Germany and World War II bombings, and finds physical capital shocks had small and temporary impacts on research output compared to large and persistent impact of human capital shocks—especially the dismissal of star scientists.

51 Triulzi, G., Alstott, J., & Magee, C. L. (2020). Estimating technology performance improvement rates by mining patent data. *Technological Forecasting and Social Change*, *158*, 120100.

But at the long-term aggregate level, while growth rates in the US have been remarkably stable, the number of researchers has increased enormously—twenty-three-fold since 1930.[52] More recently the number of researchers employed in the United States climbed 150 percent between 1980 and 2015 but we will see productivity growth has been slowing. The same story appears true for China and Germany, and, at least outside manufacturing, for Japan as well.[53]

Getting to the frontier

Why is this? Think of the capital investment Newton needed to make in order to figure out the laws of gravity. Some pens and straight edges, perhaps the opportunity cost of a piece of fruit. Even 160 years later, Ernest Rutherford's 1911 paper on the nucleus of the atom in was sole-authored, and the research infrastructure largely consisted of a source of alpha radiation, some gold foil, a screen coated with zinc sulfide, a dark room and a research assistant. Compare the two papers announcing the discovery of the Higgs particle, which had a combined total of about 2,000 authors.[54] That reflects the fact that finding the Higgs particle simply took immensely more complex empirical science that include a 27 kilometer ring of superconducting magnets crossing the Franco-Swiss border that consumes 1.3 terawatt hours of electricity a year but also a full-time team of 2,500 supported by an additional 15,000 people worldwide.[55]

A list of 2,000 authors suggests the number of discrete skills involved in reaching the frontier, and the fact that no one person, or even a small group of people, is likely to have all of the knowledge and skills required to reach it.[56] Newton coined the idea of standing on the shoulders of giants, but there were fewer giants to clamber up in the Seventeenth Century. Since then, the human pyramid has grown from Djoser to Giza-like proportions. As we have seen, young people have to wait longer to get to the knowledge frontier: Nobel-prizewinning work is occurring later and the age at first patentable innovation in the US is trending upwards at 0.6 years per decade.

But in addition, individuals reach an ever-smaller part of the frontier. Technological advance is no longer about Renaissance men inventing new techniques of perspective in the morning and new understandings of the pulmonary system in the afternoon, nor even Nineteenth Century engineers like Brunel building paddlewheel liners, designing suspension bridges, laying out railway lines,

52 Bloom, N., Jones, C. I., Van Reenen, J., & Webb, M. (2020). Are ideas getting harder to find? *American Economic Review*, *110*(4), 1104–44.

53 Boeing, P., & Hünermund, P. (2020). A global decline in research productivity? Evidence from China and Germany. *Economics Letters*, *197*, 109646. See also Miyagawa, T., & Ishikawa, T. (2019). *On the Decline of R & D Efficiency*. Tokyo: RIETI.

54 Collison, P., & Nielsen, M. (2018). Science is getting less bang for its buck. *The Atlantic*.

55 CERN website: https://home.cern/about/who-we-are/our-people https://home.cern/sites/default/files/2018-07/factsandfigures-en_0.pdf accessed 10/28/2022.

56 See Jones, B. F. (2009). The burden of knowledge and the "death of the renaissance man": Is innovation getting harder? *The Review of Economic Studies*, *76*(1), 283–317.

and designing mobile hospitals.[57] The number of innovators who patent in different fields over time (aeronautics and hydraulics, as it might be—topics that Leonardo DaVinci managed to straddle with ease) is declining.[58] The combination of working longer to reach a smaller part of the frontier implies a shrinking number of years of creativity in ever narrower fields for new innovators.

Transactions costs of cooperation

The cooperation increasingly central to breakthroughs comes with transactions costs, further slowing advance.[59] The importance of human connections to innovation is demonstrated by Jaravel, Petkova & Bell. Looking at US patent inventors from 1996 to 2012, they find that the premature death of a member of a team of co-inventors causes a significant and long-lasting decline in the future earnings and innovation of their surviving team members.[60] That will help explain why, in the U.S., team size in patentable inventions increasing at 17% per decade, and there is similar evidence of growing research teams in a range of academic fields as well as an increasing quality premium for team-based versus solo innovation.[61] The growing need for a 'creativity ecosystem' may also be why researchers increasingly physically cluster together close to colleagues and competitors, even while modern communications technologies have made collaboration over distance considerably more straightforward.[62]

And while advances in communications may have considerably increased the choice of potential collaborators, the actual act of collaboration still takes the same time. People don't talk faster over a coffee or glass of wine than they used to, or even read emails much faster than they read early typescript. Again, it is really hard for the average person to keep in contact with more than about 200 people, so that collaborations involving thousands have to involve second- and third-hand connections, with the multiplying transactions costs implied. Mounting financial and transactions costs of big projects will be one reason why a survey of principal investigators of US federally funded

57 The pure scale of much modern scientific research also limits the competitive or serendipitous discovery process. If not Newton, it is likely someone else would come up with his laws in time, even if perhaps under a different tree. It seems somewhat more doubtful that whatever knowledge the Hadron Collider produces could be produced without something that looks a bit like the Hadron Collider, and the world doesn't have very many.

58 Jones, Benjamin F. (2009). "The burden of knowledge and the "death of the renaissance man": Is innovation getting harder?" *The Review of Economic Studies, 76*(1), 283–317.

59 Bloom, N., Jones, C. I., Van Reenen, J., & Webb, M. (2020). Are ideas getting harder to find? *American Economic Review*, *110*(4), 1104–44.

60 Jaravel, X., Petkova, N., & Bell, A. (2018). Team-specific capital and innovation. *American Economic Review*, *108*(4–5), 1034–73.

61 Jones, Benjamin F. (2009). "The burden of knowledge and the "death of the renaissance man": Is innovation getting harder?" *The Review of Economic Studies*, *76*(1), 283–317. Ahmadpoor, M., & Jones, B. F. (2019). Decoding team and individual impact in science and invention. *Proceedings of the National Academy of Sciences*, *116*(28), 13885–13890.

62 Paunov, C., Guellec, D., El-Mallakh, N., Planes-Satorra, S., & Nüse, L. (2019). *On the concentration of innovation in top cities in the digital age* (No. 85). OECD Publishing. Florida, R., Adler, P., & Mellander, C. (2017). The city as innovation machine. *Regional Studies*, *51*(1), 86–96. Picci, L. (2010). The internationalization of inventive activity: A gravity model using patent data. *Research Policy*, *39*(8), 1070–1081.

research projects found that 44% of their working hours associated with those projects was spent on meeting administrative and other requirements rather than conducting active research.[63]

Aging

Aging populations linked to better health and declining fertility may be another factor behind reduced innovation. Lower fertility in one decade reliably translates into lower labor force growth two decades later, and Harvard's Nicole Maestas and colleagues use this regularity to unpack the relationship between population aging and growth across US states. They suggest that, between 1980 and 2010, aging accounted for a 0.3 percentage point decrease in the annual rate of growth over a time period when the average growth rate was 1.8 percentage points. But only one-third of that is the direct effect of slower labor force growth. Two-thirds of the reduction is because of lower labor *productivity* growth across all ages.[64] Analysis by the IMF suggests that in the past few decades, a rising share of the older workforce may have reduced European total factor productivity (TFP) growth by a tenth of a percentage point a year, and moving forward this effect may double.[65]

One mechanism will be that a shrinking, aging labor force is associated with a declining rate of new firm creation.[66] Looking at the share of entrepreneurs across countries (defined as "manages and owns a business that is up to 42 months old and pays wages"), a 3.5 year rise in the median age results in a 2.5 percentage point decline in the entrepreneurship rate—over 40 percent of the mean entrepreneurship rate across countries.[67] Faith Karahan and colleagues studied the declining rate of firm startup in the US and suggest the change in the labor supply growth rate could account for 40 to 70 percent of the change in the startup rate between 1979–81 and 2005–07. Back in 1976, about seventeen new businesses were created for every hundred existing enterprises and about 13 out of 100 businesses closed. By 2015, that was down closer to ten new arrivals and eight closures. Similarly, in 1976, about 22 new jobs were created for each existing job while 15 jobs disappeared. By 2014 that

63 Schneider, S. L., Ness, K. K., Rockwell, S., Shaver, K., & Brutkiewicz, R. (2014). 2018 Faculty Workload Survey.

64 Maestas, N., Mullen, K. J., & Powell, D. (2016). *The effect of population aging on economic growth, the labor force and productivity* (No. w22452). National Bureau of Economic Research.

65 Aiyar, M. S., & Ebeke, M. C. H. (2016). *The impact of workforce aging on European productivity*. International Monetary Fund. Based on past estimates of aging on TFP, an aging workforce in the euro area could further lower TFP growth by about 0.2 percentage points each year between 2014 and 2035. Lisenkova, K. (2020). Demographic ageing and productivity. In *Productivity Perspectives*. Edward Elgar Publishing. Note also retirees tend not to save. Looking at fourteen OECD countries between 1960 and 1985, a shift of 1% of the population from working age (20–64) to elderly (65+) reduced the private savings rate by between 0.5 and 0.9 percentage points of GDP.

66 Vollrath, D. (2020). *Fully Grown: Why a Stagnant Economy is a Sign of Success*. University of Chicago Press. P. 144, 148. Other factors behind a generalized decline in business dynamism (firm entry and exit, job creation and destruction) over the last two decades according to the OECD include the rising importance of digital technologies and intangible assets (such as R&D, patents, software and databases, etc.), possible declines in knowledge diffusion (e.g. due to strategic behaviour reflected in patent thickets or to lack of capabilities such as skills or investment capacity) Calvino, F., C. Criscuolo and R. Verlhac (2020), "Declining business dynamism: Structural and policy determinants", *OECD Science, Technology and Industry Policy Papers*, No. 94, OECD.

67 Liang, J., Wang, H., & Lazear, E. P. (2018). Demographics and entrepreneurship. *Journal of Political Economy*, *126*(S1), S140–S196.

was down to 14 and 12 (though note the pandemic and post-pandemic period saw both job churn and new startups increase).[68]

A declining population made up of ever-older people will also be less individually creative than a young and growing population.[69] Psychological and medical research suggests cognitive abilities reach maximum level in the 20s and early 30s, declining considerably by the age of 50. Similarly, studies of research and innovation output point to productivity peaks in the thirties and forties.[70] We have seen there is a rising minimum age commensurate with having reached toward some frontiers of knowledge: Nobel Prize winning contributions before age 26 are extremely rare, and none have involved work begun earlier than age 19, and we've seen it is taking longer for Nobelists to complete their PhDs. But there's also a peak of creativity not long thereafter.[71] A study of 2,026 notable scientists and inventors from antiquity to the 20th century found that contributions peak on average at age 39. Again, a dataset of the ages of 1.2 million U.S.-resident inventors patenting between 1976 and 2017 suggest that patenting rates peak at around the early 40s.[72]

Kalyani finds that 'creative' patents associated with improvement in stock market valuations and firm-level productivity are considerably more likely to be filed by first-time inventors, and suggests that falling population growth (and so fewer new inventors) might account for as much as 42 percent of the observed decline in US patent creativity (which is that the average patent in 2018 is less than half as creative as a patent in 1981) and 32 percent of the recent decline in productivity growth.[73]

As with research and development, and doubtless for similar reasons, peak entrepreneurial potential appears to be in young middle age.[74] Or look at other creative fields: Paul McCartney wrote *Yesterday* at 23, co-wrote *She's Leaving Home* at age 25, but was reduced to writing *We All Sing Together* with the

68 Karahan, F., Pugsley, B., & Şahin, A. (2019). *Demographic origins of the startup deficit* (No. w25874). National Bureau of Economic Research. Meanwhile the share of employment of firms with 250 employees or more in the US has increased by six percentage points since 1978 Hopenhayn, H., Neira, J., & Singhania, R. (2018). *From population growth to firm demographics: Implications for concentration, entrepreneurship and the labor share* (No. w25382). National Bureau of Economic Research. On the pandemic period see Kauffman data: https://indicators.kauffman.org/indicator/rate-of-new-entrepreneurs/2020. Accessed 10/28/2022.

69 Calvino, F., C. Criscuolo and R. Verlhac (2020), "Declining business dynamism: Structural and policy determinants", *OECD Science, Technology and Industry Policy Papers*, No. 94, OECD. Lui, S., Black, R., Lavandero-Mason, J., & Shafat, M. (2020). Business Dynamism in the UK: New Findings Using a Novel Dataset (Working Paper No. ESCoE DP-2020–14). Economic Statistics Centre of Excellence (ESCoE).

70 Lisenkova, K. (2020). Demographic ageing and productivity. In *Productivity Perspectives*. Edward Elgar Publishing.

71 Jones, B., Reedy, E. J., & Weinberg, B. A. (2014). Age and scientific genius (No. w19866). National Bureau of Economic Research. (The increasing rate of later lifecycle achievements is driven by an aging population, not by rising productivity at older ages increased productivity at later ages).

72 For solo inventors, citing other patents increased with age, suggesting the value of experience, while the number of inventors citing the patent itself as well as other measures of the utility of the patent declined with age, suggesting novelty in innovation may be a feature of youth. Kaltenberg, M., Jaffe, A. B., & Lachman, M. E. (2021). Invention and the Life Course: Age Differences in Patenting (No. w28769). National Bureau of Economic Research.

73 Aakash Kalyani. (2022). The Creativity Decline: Evidence from US Patents, Working Paper, Boston University.

74 Liang, J., Wang, H., & Lazear, E. P. (2018). Demographics and entrepreneurship. *Journal of Political Economy*, *126*(S1), S140–S196.

Frog Chorus at 46. Mozart died at age 35, surely a tragic loss to friends and family, but perhaps it saved him from writing for the *Frosh Concerto*.

Despite the greater creativity of younger innovators, research funding is increasingly directed toward older researchers, an institutional failing that increases the impact of an aging workforce on outputs. Since a 1994 change in US law, universities have been prohibited from forcing faculty to retire at age 70. Given many have tenure, that means they can go on until they drop. From 1971 to 1993, 1% of US faculty were over 70. From 1994 onward, an average of 14% of faculty were over 70.[75] And as it is easier to get grants renewed rather than apply for the first time, this has further entrenched the dominance of old researchers. Looking at the National Institutes of Health research budget of about $30 billion annually in grants,[76] in 1980, 21 percent were awarded to researchers under the age of 35. That has declined to below two percent. Meanwhile the share awarded to those over 65 has increased from below one percent to nearly ten percent. The average age at first grant award has increased from 34 years old to 44 years old since 1970.[77]

Pierre Azoulay and colleagues summarize the problem of an aging research community rather macabrely in their paper title "Does Science Advance One Funeral At a Time?" in which they find premature death of a star scientist is followed by a flow of papers into their field by new authors who write papers that are highly cited. "[O]ur results suggest that once in control of the commanding heights of their fields, star scientists tend to hold on to their exalted position a bit too long," they conclude.[78]

Risk averseness

Along with 'supply side' issues regarding the number and abilities of innovators, as well as the increasing complexity of creating new ideas, there are 'demand side' issues including the appetite for risk and the kind of innovations that people want. A number of studies of health behavior conclude that people with shorter life expectancy will take greater health risks—the assumption being, what have they got to lose? But the reverse also applies: people who can otherwise expect a long, comfortable lifestyle are likely to be less inclined to risk it.[79] And the value of a statistical life goes up

75 Again, 37% of faculty are 55 or older, compared to 23% of all U.S. workers. Data from College and University Professional Association for Human Resources https://www.cupahr.org/surveys/research-briefs/2020-aging-of-tenure-track-faculty-in-higher-ed-implications-for-succession-diversity/ accessed 10/28/2022.

76 Data from National Institutes of Health https://newscience.org/nih/ accessed 10/28/2022.

77 Data from National Institutes of Health https://newscience.org/nih/ accessed 10/28/2022.

78 Azoulay, P., Fons-Rosen, C., & Graff Zivin, J. S. (2019). Does science advance one funeral at a time? *American Economic Review*, *109*(8), 2889–2920.

79 Oster, E. (2012). HIV and sexual behavior change: Why not Africa? *Journal of Health Economics*, *31*(1), 35–49. Godlonton, S., Munthali, A., & Thornton, R. (2016). Responding to risk: Circumcision, information, and HIV prevention. *Review of Economics and Statistics*, *98*(2), 333–349. Kerwin, Jason. "Scared straight or scared to death? The effect of risk beliefs on risky behaviors." *The Effect of Risk Beliefs on Risky Behaviors (February 9, 2018)* (2018).

as countries get richer, in approximate lockstep with GDP.[80] In turn that drives greater regulation and control of risks, which in turn may reduce the potential to innovate.

It is broadly a good thing that we are becoming more risk averse, in that it is a force for reduced violence and the regulation of perils. But emphasizing the preservation of existing material comfort and security is not the strongest force for technological and societal progress, and regulation can carry deadweight costs. The recent Covid-19 pandemic provides examples. While vaccines were created in record time, FDA regulatory decisions significantly delayed the availability of tests, for example.[81] Similarly, the Nuclear Regulatory Commission has to be held somewhat accountable for the fact that only one commercially operating power reactor in the US is less than twenty years old.[82] Or, with regard to Internet innovation in Europe, looking at 4.1 million apps at the Google Play Store from 2016 to 2019, the EU's General Data Protection Regulation induced the exit of about a third of available apps; and in the period following implementation, entry of new apps fell by half. [83]

The innovation we want

Perhaps even more significant is the fact that the progress we are continuing to make in research remains concentrated in the creation of stuff (reflected not least in the continually declining cost of equipment)[84] while what we want to consume is increasingly not stuff, but services like education, care and entertainment.

Services now account for two thirds of global GDP (and 80 percent of US GDP).[85] The trend will continue as economies age: within the US, compared to households in their early 30s, the service expenditure shares of households in their early 60s are 8 percentage points higher, and the service shares of expenditures of those over 80 are 27 percentage points higher. (Major drivers of the change are that young people spend more on cars while old people spend more on health and domestic

80 Viscusi, W. K., & Aldy, J. E. (2003). The value of a statistical life: a critical review of market estimates throughout the world. *Journal of Risk and Uncertainty*, *27*(1), 5–76. Miller, Ted R. (2000). "Variations between countries in values of statistical life." *Journal of Transport Economics and Policy*, 169–188.

81 March, R. J. (2021). The FDA and the COVID-19: A political economy perspective. *Southern Economic Journal*, *87*(4), 1210–1228.

82 Data from Nuclear Regulatory Commission: https://www.nrc.gov/docs/ML2130/ML21300A286.pdf p.31 accessed 10/28/2022. A non-innovation-related example is road infrastructure: real spending per mile on Interstate construction increased more than threefold from the 1960s to the 1980s. The major factors don't appear to have been per unit labor or materials prices, but instead increases in income, housing prices and "citizen voice" in government decision-making. States construct more ancillary structures (bridges and ramps), and interstates take more wiggly routes in later years of the program when mandated environmental review and citizen input became widespread. Brooks, Leah, and Zachary Liscow. "Infrastructure costs." In *111th Annual Conference on Taxation*. NTA, 2018.

83 Janssen, R., Kesler, R., Kummer, M. E., & Waldfogel, J. (2022). *GDPR and the lost generation of innovative apps* (No. w30028). National Bureau of Economic Research.

84 Jones, C. I. (2016). The facts of economic growth. In *Handbook of Macroeconomics* (Vol. 2, pp. 3–69). Elsevier.

85 Data from World Bank World Development Indicators https://data.worldbank.org/indicator/NV.SRV.TOTL.ZS accessed 10/28/2022.

services.)[86] Across countries, and after controlling for income, a 1 percentage point increase in the fraction of population that is over 65 is associated with a 1.3–1.5 percentage point increase in the service shares of value-added and employment.[87]

We have seen that with education, productivity growth has traditionally been very slow—and the same applies to a considerable part of the services sector.[88] That suggests not only are ideas becoming harder to find, we want to find harder ideas. More and more of the progress we went requires breakthroughs not from the insight of chemists and engineers but the sort of advance you might hope would come from politicians, lawyers, accountants, restauranteurs, educators, healthcare mangers and social scientists, and it isn't clear these groups are up to the challenge. Sixty-nine percent of US Business R&D in 2009 (the latest year for which the OECD has data) was still in manufacturing (another 16 percent was in 'computer and related activities'). Most other parts of the economy barely get a look-in.[89] Again, more than 70 percent of U.S. corporate patents are in manufacturing.[90]

We have simply been better at doing research on practical ideas to make things more efficient or make new things in the stuff space than the 'not stuff' space. A lot of the 'not stuff' space is about social interactions and public goods where there isn't enough data to conclusively answer questions and test advances even in a single context. And with material progress, research pays off, and often pays off globally: Creating fertilizer using the Haber-Bosch process works everywhere, vaccines work everywhere (even if the institutions and infrastructure to deliver them does not). But with non-material progress science often doesn't work so well or translate so easily to other contexts or lead to a product that can be marketed. We have a problem of statistical power regarding the macro

86 Looking at health care in particular, the diminishing marginal utility of non-health consumption combined with a rising statistical value of life both encourage greater spending on worldwide. Projections based on past spending growth suggest that health expenditures alone in the US may reach 33 percent by the middle of the centuryHall, R. E., & Jones, C. I. (2007). The value of life and the rise in health spending. *The Quarterly Journal of Economics*, *122*(1), 39–72. And despite the fact the relationship between health care spending and actual health is tenuous, circumstances will force the trend onwards. Not least, across 30 high income countries, the share of the population that will likely rely on long-term care (in that they are elderly and have mobility or other disabilities that constrain self-reliance) will rise from 2.9 of the population to 4.2 percent between 2020 and 2040. Kotschy, R., & Bloom, D. E. (2022). *A Comparative Perspective on Long-Term Care Systems* (Working Paper No. 15228). Institute of Labor Economics (IZA).

87 Cravino, J., Levchenko, A. A., & Rojas, M. (2019). Population aging and structural transformation (No. w26327). National Bureau of Economic Research.

88 William Nordhaus estimates that over the period 1948–2001, the shift to lower productivity sectors has knocked 0.64 percent off growth rates. Nordhaus, W. D. (2008). Baumol's diseases: a macroeconomic perspective. *The BE Journal of Macroeconomics*, *8*(1). According to economists Georg Duernecker and Miguel Sanchez-Martinez "the secular rise of the service sector is a central element in explaining the dismal productivity performance of EU countries over relatively long historical periods." Food, business services, education and health appear particularly stagnant. That these slow-growth sectors have taken an ever-larger share of output has knocked 0.4 percentage points off growth in Europe over the period 1970–2017. Duernecker, G., & Sanchez-Martinez, M. (2021). *Structural Change and Productivity Growth in Europe-Past, Present and Future* (No. 9323). CESifo Working Paper.

89 Data from the OECD https://stats.oecd.org/Index.aspx?DataSetCode=BERD_INDUSTRY accessed 10/28/2022.

90 Jones, C. I. (2022). The past and future of economic growth: A semi-endogenous perspective. *Annual Review of Economics*, *14*, 125–152.

(not enough data to introduce evidence-based improvement in national institutions, as it might be)[91] and a problem of replicability regarding the micro (the schooling intervention that works as a pilot in Boston might not work at scale in Mexico).[92] And it is more difficult to separate out services innovations that are purely private good rather than public good (in that they shift rather than create value): many recent financial innovations appear ultimately to have fallen into the private good category.[93] All of this will help to explain why recent reviews suggest we know even less than we thought we did in social sciences, for example, and we didn't know all that much in the first place.[94]

Technology advance is slowing

To be fair to researchers in service delivery, the problem may also be significantly on the demand side: people simply aren't very good at consuming services, still taking a similar time to watch a movie, read a book or enjoy a concerto as their parents. But wherever the fault ultimately lies with regard to slowing innovation per educated person, we certainly appear to have a problem. In 2005, Jonathan Huebner studied a list of 8583 important events in the history of science and technology and suggested that the rate of innovation reached a peak as long as a hundred years ago. He concludes "This decline is most likely due to an economic limit of technology or a limit of the human brain that we are approaching. We are now approximately 85% of the way to this limit, and the pace of technological development will diminish with each passing year."[95]

This is one, eminently arguable, measure, but others point in the same direction. Economist Thomas Philippon has looked at past patterns of TFP growth in the US as a whole and for private firms and then for 23 advanced countries over 129 years–and in all three cases he suggests that total factor productivity grows in a pattern that usually looks additive rather than exponential. That implies slower growth rates in future.[96]

There are good reasons to cast doubt on the scale of the productivity slowdown. Not least, we are increasingly buying things that used to be outside the GDP statistics: cooking, cleaning, care services.

91 Kenny, C., & Williams, D. (2001). What do we know about economic growth? Or, why don't we know very much? *World Development*, *29*(1), 1–22.

92 Ioannidis, J. P., Stanley, T. D., & Doucouliagos, H. (2017). The Power of Bias in Economics Research. *Economic Journal*, *127*(605), 236–265. Arel-Bundock, Vincent, et al. "Quantitative Political Science Research Is Greatly Underpowered." OSF Preprints, 5 July 2022. Pritchett, L., & Sandefur, J. (2015). Learning from experiments when context matters. *American Economic Review*, *105*(5), 471–75.

93 Cowen, T. (2011). *The great stagnation: How America ate all the low-hanging fruit of modern history, got sick, and will (eventually) feel better: A Penguin eSpecial from Dutton*. Penguin.

94 For example: "We compared the behavioral scientists' predictions to random chance, linear models, and simple heuristics like "behavioral interventions have no effect" and "all published psychology research is false." We find that behavioral scientists are consistently no better than - and often worse than—these simple heuristics and models." Bowen, Dillon, (2022), Simple models predict behavior at least as well as behavioral scientists, Papers, arXiv.org, https://EconPapers.repec.org/RePEc:arx:papers:2208.01167.

95 Huebner, J. (2005). A possible declining trend for worldwide innovation. *Technological Forecasting and Social Change*, *72*(8), 980–986.

96 Philippon, T. (2022). *Additive Growth* (No. w29950). National Bureau of Economic Research.

That has made GDP statistics more reflective of real life, suggesting some of the productivity slowdown is actually more about better reflecting an economy that was never changing as fast as it looked. It also suggests some of the rising demand for non-stuff is just rising demand for non-stuff *provided by the market*. Again, the impact of the Internet and the free goods it provides is imperfectly accounted for in the statistics.

At the same time, we all have dining rooms and kitchens and now so do a *lot* of restaurants—our capital is working less hard, and there are transactions costs of contracting out incompletely contractable work. And these activities are all still low productivity. And it appears that even accounting for mismeasurement, the TFP slowdown is real. Not least, the productivity slowdown is a phenomenon across multiple countries with very different consumption patterns, and estimates of the surplus created by Internet applications like Google fall considerably short of the $3 trillion scale of "missing output" implied by the productivity statistics (and if they didn't we'd have to be underestimating output and productivity growth rates of the involved industries by multiples).[97]

Responses

William Baumol argued that where entrepreneurs put their efforts will depend on the returns they can expect in different activities, and that will be driven by institutional factors.[98] On the positive side, this suggests creating institutional environments that encourage more entrepreneurs into the creation of public good technologies would have a payback.[99] Evidence that 'institutional quality' can impact innovation includes that higher scores on the World Bank's Worldwide Governance Indicators are associated with a higher rate of patent applications,[100] countries with more developed equity markets see more innovation in high-tech,[101] stronger shareholder protections and better access to stock market financing boost R&D investment.[102] (The relationship between intellectual property rights and innovation is less straightforward: looking at 177 changes in patent policy across

97 Syverson, C. (2017). Challenges to mismeasurement explanations for the US productivity slowdown. *Journal of Economic Perspectives*, *31*(2), 165–86.

98 Baumol, W. J. (1990). Entrepreneurship: productive, unproductive and destructive. *Journal of Political Economy, 98*(5), 893–921.

99 For example, DeLong argues that underpinning the rapid technological progress of the late 1800s and early 1900s was the creation of the industrial research lab, the large modern corporation and globalization which, between them, eased the supply and considerably increased the demand for innovation. DeLong, J. B. (2022). *Slouching towards Utopia: An economic history of the twentieth century*. Basic Books.

100 Canh, N. P., Schinckus, C., & Thanh, S. D. (2019). Do economic openness and institutional quality influence patents? Evidence from GMM systems estimates. *International Economics*, *157*, 134–169. See also Edinaldo Tebaldi & Bruce Elmslie. (2013). Does institutional quality impact innovation? Evidence from cross-country patent grant data, *Applied Economics*, *45*(7), 887–900.

101 Hsu, P. H., Tian, X., Xu, Y. (2014). Financial development and innovation: cross-country evidence. *J. Financ. Econ*, *112*(1), 116–35.

102 Brown, J. R., Martinsson, G., Petersen, B. C. (2013). Law, stock markets, and innovation. *J. Finance, 68*(4), 1517–49.

60 countries over 150 years Lerner finds little evidence that stronger patent laws increase rates of innovation).[103]

And we can simply throw more money at the problem: worldwide, R&D as a proportion of GDP averages about 2.63%, but some countries see shares of 5% or more, with government support explaining a good deal of the variance.[104] And government subsidy of early-stage innovation is associated with the financing, success, and profitability of innovative companies.

But it may be that fostering greater equality of opportunity to innovate has the largest long-term potential to sustain technological advance. In the US, children from high-income (top 1%) families are 10 times as likely to become inventors (patent holders) as those from below-median income families, and the gap is not explained by differences in math test scores.[105]

Looking at gender discrimination, there is still opportunity in (and moral responsibility to deliver on) greater gender equality, particularly in some parts of the innovation ecosystem. There are only seven women for each ten men in the labor force worldwide.[106] Less than twenty percent of firms worldwide are managed by women.[107] Despite the fact that the proportion of women over 25 with tertiary education in the US was higher than the proportion of men with that level of education in 2010,[108] the proportion of US patents including at least one woman inventor was still only 18.8 percent in that year, and under 8 percent of all patents have women as primary inventors, with particularly stark gaps in engineering-related patents.[109] Worldwide, only 23 percent of international patents list a woman as one of the innovators.[110] Given discrimination, it is perhaps not surprising that Kalyani finds women and ethnic minorities file patents which are more creative (linked to greater firm productivity) than others in the US.[111]

Equalizing the opportunity to innovate across countries might have even larger effects. Many participants in the International Math Olympiad competition for young mathematical talents go on to successful academic careers. But Olympiad participants from a low-income country go on to produce

103 Lerner, J. (2009). The empirical impact of intellectual property rights on innovation: puzzles and clues. *Am. Econ. Rev. Pap. Proc.*, *99*(2), 343–48.

104 World Bank World Development Indicators https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS accessed 10/28/2022, Thomson, R. (2017). The effectiveness of R&D tax credits. *Review of Economics and Statistics*, *99*(3), 544–549.

105 Alex Bell, Raj Chetty, Xavier Jaravel, Neviana Petkova, John Van Reenen, Who Becomes an Inventor in America? The Importance of Exposure to Innovation, *The Quarterly Journal of Economics*, Volume 134, Issue 2, May 2019, Pages 647–713.

106 World Bank World Development Indicators https://data.worldbank.org/indicator/SL.TLF.CACT.FM.ZS, accessed 11/18/2022.

107 World Bank Enterprise Survey data, https://www.enterprisesurveys.org/en/data/exploretopics/gender accessed 11/18/2022.

108 Barro-Lee dataset, available at http://www.barrolee.com/ accessed 10/28/2022.

109 CGD Blog https://www.cgdev.org/publication/expanding-womens-role-developing-technology accessed 10/28/2022.

110 WIPO https://www.wipo.int/women-and-ip/en/news/2022/news_0001.html#:~:text=In%202021%2C%20women%20were%20listed,%25)%20and%202021%20(17.7%25) accessed 10/28/2022.

111 Aakash Kalyani. (2022). The Creativity Decline: Evidence from US Patents, Working Paper, Boston University.

35% fewer mathematics publications (and those publications are less cited) than an equally-scoring Olympiad participant from a high-income country. It is not that they simply chose to excel elsewhere than academia—although fewer do end up as professors. Instead, suggest study authors Ruchir Agarwal and Patrick Gaule, these talents simply become 'invisible.' If we could fix the global problem of invisible talent, we could considerably increase knowledge generation at the frontier.

An expanding base of quality research institutions in developing countries approaching the technology frontier is a sign that this problem is already diminishing. Using the imperfect measure of resident patent applications per million people, in developing countries this has climbed from 4.5 to 168 per year between 1985 and 2015, or from one percent of the high-income patenting rate to 25 percent of the high-income patenting rate.[112] But that is still a big gap, and removing China from the developing country data makes it considerably larger still.

Moving potential innovators and entrepreneurs to frontier countries is an additional way to achieve the same result of increased potential to innovate.[113] The greater productivity of leading researchers in the US and the global spillover benefits of knowledge creation suggests greater US openness to researchers would be of considerable worldwide benefit.[114] First generation immigrants create about 25% of new firms in the US and account for between a fifth and a third of the global stock of Nobel Prize winners and Fields Medalists (awarded to leading mathematicians).

Charles Jones estimates that if the global population of researchers increased by a factor of 7 over the course of the century that could add 0.4 percent a year to growth rates. This should be comparatively straightforward in a world of increasing wealth, gender equality and greater freedom of movement.

Still, at some point, even if we trend toward Jones' target, the growth in researcher numbers will begin to decline. Indeed, research intensity is already rising more slowly than it was: For the OECD, research employment grew at 4.1% per year 1981- 2003 but only 2.8% per year since then.[115] And migration may be only a temporary fix. Worldwide, there is an inverted u-shaped relationship between emigrant stocks and income, peaking at a per capita GDP of about $10,000 dollars. By 2050, more than 70 percent of the global population will live in a country with a GDP per capita that is greater than that, and if the current relationship persists, this suggests a declining stock of global immigrants to power innovation in countries at the technological frontier.[116]

112 Calculated from Our World in Data: https://ourworldindata.org/grapher/patent-applications-per-million accessed 10/28/2022.

113 Agarwal, R., & Gaule, P. (2020). Invisible geniuses: could the knowledge frontier advance faster? *American Economic Review: Insights*, *2*(4), 409–24.

114 Kerr, S. P., & Kerr, W. (2020). Immigrant entrepreneurship in America: Evidence from the survey of business owners 2007 & 2012. *Research Policy*, *49*(3), 103918. Agarwal, R., Ganguli, I., Gaulé, P., & Smith, G. (2021). Why US Immigration Barriers Matter for the Global Advancement of Science. *Available at SSRN 3762886*.

115 Jones, C. I. (2022). The past and future of economic growth: A semi-endogenous perspective. *Annual Review of Economics*, *14*, 125–152.

116 Kenny, Charles, and George Yang. *Can Africa Help Europe Avoid Its Looming Aging Crisis?* Center for Global Development, 2021.

Perhaps eventually artificial minds will come to the rescue, but progress in artificial intelligence challenges appears to be limited even in an age of rapid growth in computing power: while more powerful computers explain 49%-94% of the performance improvements that computers have demonstrated in playing Chess and Go, predicting the weather, folding proteins and oil exploration, it has taken an exponential increase in computing power to get linear improvements in outcomes.[117] This frustrated ambition may help explain the recent outbreak of violence at a Russian chess competition between a robot and a seven year old boy, in which the robot grabbed the finger of its human opponent and broke it: an approach to victory potentially requiring less processing power.[118] Robots aren't currently delivering anything like the kind of research productivity impact required to make up for the slowdown in the growth rate of innovators, and there is little sign of that changing soon.[119]

Conclusion

It is far from impossible we will see a reverse to a period of greater material scarcity on the one hand or toward greater capacity to both produce and consume material and non-material progress on the other.

Progress may not remain relatively unconstrained by 'natural limits.' The developing world is still seeing rising material consumption, and a major question for the future is whether our progress in efficiency will be fast enough to make a high quality of life for all globally sustainable. Beyond greenhouse gasses, wild fish catch has begun to fall not because of limits to demand but because fish stocks are so depleted it is hard to find more.[120] On land, we are yet to reach peak soil loss and we are some way from slowing species extinction.

But there is at least a path to high- income sustainability where the world finds itself in what British economist Kate Raworth calls the 'donut': consumption sufficient for all to enjoy material abundance, generated without overstepping planetary environmental boundaries.[121] The technological change we're still relatively good at—the material change—is what is really important for keeping human populations within 'carrying capacities.'

Combined with a rapidly peaking global population that suggests, if there is a 'progress problem,' it is probably not primarily one involving humanity's relationship with nature. In fact, while it is far more common to worry about the negative externalities of humans, in a world of declining population,

117 Thompson, Neil C., Shuning Ge, and Gabriel F. Manso. "The importance of (exponentially more) computing power." *arXiv preprint arXiv:2206.14007* (2022).

118 The Guardian: https://www.theguardian.com/sport/2022/jul/24/chess-robot-grabs-and-breaks-finger-of-seven-year-old-opponent-moscow accessed 10/28/2022.

119 Leitner, S. M., & Stehrer, R. (2019). *The automatisation challenge meets the demographic challenge: In need of higher productivity growth* (No. 171). wiiw Working Paper.

120 Our World in Data Fish and Fishing https://ourworldindata.org/fish-and-overfishing accessed 10/28/2022.

121 Raworth, K. (2017). *Doughnut economics: seven ways to think like a 21st-century economist*. Chelsea Green Publishing.

we should be more increasingly worried about the positive externalities going away. If Simon was right 40 years ago, he is increasingly right today.

An aging, declining human population faces an ever-harder challenge to find new ideas. Sustaining the rate of progress we have grown used to will take change: medical advance may well extend our period of peak creative capacity, supported by greater artificial intelligence. And perhaps we will reverse course in fertility trends so that there will be more people to live longer and more creative lives. We can fix the problem that boys born to rich, white parents living in a rich country still have magnitudes the chance to grow up to build a global company or invent a new cancer drug than do minority girls born to relatively poor parents in the poorest countries. The more we level up the global opportunity to innovate, the longer rapid progress can continue—perhaps for centuries.

Furthermore, even if that doesn't happen, relative stagnation will itself spread slowly, and is a sign of our earlier pace. Dieter Vollrath's book on the demographic and other forces behind slower growth in the US is subtitled "Why a stagnant economy is a sign of success" and there's a lot to that: it reflects womens' emancipation from the burden of large families and a lifetime of child-care and the fact that our material desires are reaching sufficient satiation that we'd rather spend our money on baristas making us frappucinos.

So while the central forecast for the world is for measured deceleration rather than the galactic fantasies of the techno-utopians, it is also a long way from the squalid sub-slum nightmares of much Hollywood futurology. And as that still means generations of ten billion living lives of a quality beyond the dreams of their ancestors, it isn't a bad place to end up. We will have quite enough of the ultimate resource to sustain that, at least.