Entrepreneurs Make Leaps:
A Critique of the Theory of the Adjacent Possible

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Abstract

The theory of the adjacent possible (TAP) is a combinatorial account of the growth of the biosphere and the technosphere, conceived by Stuart Kauffman, popularized by Steven Johnson, and formalized into the TAP equation by Roger Koppl, Stuart Kauffman, Abigail Devereaux, and others in their ambitious paper "Explaining Technology" (2023). The TAP equation is a curve-fitting exercise where unrealistic values of fixed parameters are assumed in order to generate the shape of the hockey stick graph of economic growth. A crucial mistake in the TAP model is that it "deflates" the agency of breakthrough inventors and especially of innovative entrepreneurs. As a result of this mistake, it fails to explain several important stylized technology facts like why the Industrial Revolution occurred first in England. Several stories document how the agency of inventors and entrepreneurs matters, including stories about William Coley, Bart Gullong, Frank Hursey, Jony Ive, Steve Jobs, Elon Musk, George Stephenson, Leo Szilard, Peter Thiel, Josiah Wedgwood, and Wilbur Wright. These stories show that technological progress is not always incremental, inevitable, or adjacent; technology does not always increase in diversity and complexity; and the inventor's and the entrepreneur's urgency, courage, and perseverance can matter. Actionable explanations of technology are most useful in speeding technological and medical progress. Empirically thick sources can improve explanations of technology. So far we know technology flourishes where institutions and policies support rule of law, property rights (including patents), limited regulations, low taxes, and respect for inventors and entrepreneurs. Some technology leaps occur

because we benefit from geniuses and because science fiction can inspire geniuses, and the rest of us, to actualize dreams that currently are not part of the adjacent possible.

1. **Introduction**

Both the biosphere and the technosphere have experienced explosions, in the biosphere the explosion of life that started with the Cambrian period and in the technosphere the explosion of technologies or gross domestic product (GDP) that started with the Industrial Revolution around 1800 CE. At least until recently, almost everyone has wanted the growth that started with the Industrial Revolution to continue, so a true and actionable explanation of the Industrial Revolution has been the Holy Grail of economics.[1]

The theory of the adjacent possible (TAP), as originally stated by Stuart Kauffman to explain the growth in diversity of the biosphere (Kauffman 2000, pp. 142-144), was a natural explanation, built on Darwin but going beyond Darwin, and involving no human agency. When Roger Koppl joined Kauffman and co-authors to discuss the TAP, they repurposed the theory to apply it to economic goods (Koppl et al. 2015). "Toward an entrepreneurial economics" (p. 21) was a sub-heading of their 2015 paper, clearly affirming the centrality of human agency. Since entrepreneurial action mattered, the co-authors also aimed to understand what policies constrained or enabled the entrepreneurs. They wrote, for instance, that "A central task in entrepreneurial economics is to ask what institutions and laws . . . promote favorable entrepreneurial opportunities" (Koppl et al. 2015, p. 25).

Three years later, in 2018, when Kauffman and Koppl with a new pair of co-authors first formalized the TAP by adding the TAP equation (Koppl et al. 2018), the role of human agency became less clear. In this 2018 paper, they state that their TAP equation “*deflates* competing views” (Koppl et al. 2018, p. 5; *their* italics) and claim that the Industrial Revolution is “independent of any special cultural, *institutional*, or genetic causes” (Koppl et al. 2018, p. 5; *my* italics). In three years understanding institutions has been deflated from “a central task” to irrelevance.

Five years passed before the publication in 2023 of what I take to be the currently canonical account of the TAP equation, the long paper (or short book) “Explaining Technology” in the Cambridge Evolutionary Economics Elements series (Koppl et al. 2023). The account is rich with erudition, broad with topics, and crowded with Kauffman and Koppl co-authors, including both of the pair of co-authors of the 2018 paper, but neither of the pair of co-authors of the 2015 paper. The crowd of co-authors added to the cumulative erudition and breadth but understandably may have come at the cost of occasional disagreement among co-authors. The co-authors acknowledge, for example, that they do not agree on the severity and implications of global warming (Koppl et al. 2023, p. 27).

The role, or lack of role, of human agency in the evolution of technology implied by the TAP equation may be another issue on which the co-authors disagree, or alternatively, Kauffman, Koppl, or some of their co-authors may be internally conflicted on the issue. One or the other must be true, because at some points in the paper human agency is absent, while at other points humans have something to do.

If we say that the TAP “model” consists of the TAP equation and the words that are used to describe it, then a “core version” of the model eschews human agency, while an “augmented version” of the model allows for some limited roles for human action.

Several passages in "Explaining Technology" tend to support the core version. For instance, ". . . automobiles are not the product of foresight and rational planning. They emerge from the division of labor like stones heaved out of the New England soil by an autumnal frost" (Koppl et al. 2023, p. 13). Under the sub-heading of "Genius" the co-authors briefly deny that the "solitary genius" is an important driver of new technology. They say the genius account is "obvious and naïve" (p. 5). They say it supposes "ideas are inexplicable gifts from the brow of genius" (p. 5). They say the genius account is common "outside academia" (p. 5). They say it features a "mad scientist" such as "Dr. Frankenstein" (p. 5). They say it is "passed on to the masses" in folk stories like *Prometheus* (p. 6). Before their brief denial of genius, they had earlier said genius plays a role, "but recombination is the essential driver of technological evolution" (p. 3). The implication of this last passage is that genius is non-essential and could be jettisoned without effect.

In the abstract to "Explaining Technology" (p. iii) and again separately on each of pages 23 and 24, the authors say that the Industrial Revolution was "inevitable" (Koppl et al. 2023). The word "inevitable" implies that the Industrial Revolution would have happened no matter what anyone did or did not do and so supports the core version of the TAP model. Koppl et al. (2023) say that theirs is a "radically different explanation of the Industrial Revolution" that "deflates" alternative explanations (p. 24). "It was slow, grinding probability taking its own sweet time before finally delivering the inevitable combinatorial explosion" (p. 24). "Technological progress" is a "stochastic process" (p. 24). "Technology evolves when tinkering humans cobble together existing elements" (Koppl et al. 2023, p. 55).

What is at the very end of a paper often summarizes the central message of the paper, so it may be significant that at the very end of “Explaining Technology” Koppl et al. (2023) leave us with the following two sentences: “The technosphere was not designed by any rational, godlike creature, standing apart from the surge and flux of earthly life. It emerged unintendedly from the tinkering, testing, and trying of creatures but little wiser than their primate cousins” (Koppl et al. 2023, p. 59). Human action is allowed, but barely, and without high regard.

In some passages Koppl et al. (2023) express the augmented version of their model, especially in Section 7 “Homo Tinkerus” and Section 8 “Entrepreneurship and Innovation.” Section 7 is about eight pages long, while section 8 is about two pages long, accurately reflecting their “deflation” of the role of human agency in the innovation process, since “tinkerer,” which they emphasize, has a more negative connotation than “entrepreneur.” The *O.E.D.* says of the verb “tinker’ that it is “in all senses usually depreciative” and the *O.E.D.* defines “tinkerer” as “one who tinkers or works at mending something in a clumsy or ineffective way” (*O.E.D.* 1971, p. 3329). Stuart Kauffman sometimes calls tinkering “jury-rigging” (2019, pp. 120-122 and 134-139; 2023; see also Koppl et al. 2023, p. 54). The tinkerer jury-rigs together whatever elements “are just lying around” (Koppl et al. 2023, p. 49). Late in the section they want to give more depth to their account of what the tinkerer is doing, by briefly saying that he is making use of his *Suchbilden* and *Umwelten*. Their only example is how a frog’s *Suchbilden* helps it search for a fly. Human examples might help us see how these concepts apply to tinkering.

The tinkerer is briefly promoted in the penultimate Section 8 to "entrepreneur." They identify "entrepreneur" as an alert-to-opportunity Kirznerian entrepreneur.[2] Kirznerian entrepreneurs are often contrasted with Schumpeterian entrepreneurs. The Kirznerian entrepreneur brings us closer to equilibrium, making markets more efficient, while the Schumpeterian entrepreneur (unintentionally) takes us further from equilibrium by bringing breakthrough new products to the market. Both types of entrepreneur help the economy to flourish. But Koppl et al. (2023) never mention the Schumpeterian entrepreneur and do not even assign too much agency or creativity to their Kirznerian entrepreneur:

> The theory of the adjacent possible shows that opportunities are created by the system, rather than being some sort of ex nihilo creation of individual brains. At any moment, the potential combinations in the adjacent possible exist independently of the entrepreneur who "merely" *discovers* one or more of these preexisting combinations. (Koppl et al. 2023, p. 57; *their* scare quotes and italics).

And, again, they worry that we might think too highly of Thomas Edison and Steve Jobs:

> In everyday language we say Thomas Edison and Steve Jobs were "creative." But their "creativity" consisted in combining preexisting elements already present in the adjacent possible. (Koppl et al. 2023, p. 58)

Later I will present an account of Jobs that is at odds with the TAP model account, but here the only point is that the authors want to "deflate" our view of America's foremost inventors and entrepreneurs. Doing so is consistent with their earlier admission that they salute N.F.R. Crafts (1977) in viewing "'technological progress' as a 'stochastic process'" (Koppl et al. 2023, p. 24).

When applied to human history, the parameters or variables of the TAP equation can be interpreted as just as independent of human agency as they are when the equation is applied to the biosphere, or alternatively some term in the equation could be a function of human action or choice. The form and components of the TAP equation will be described in the next main section. Here it is only required to note that in their explicit exposition of the TAP equation, the parameters (*P* and the α_i*'s*) are set at fixed values, and the key dependent variable *M* is endogenous to the model, so how can human action possibly matter? The authors state that unlike alternative accounts of technology their TAP model is free of "ad hoc elements" (Koppl et al. 2023, p. 25). But their own account of tinkerers and Kirznerian entrepreneurs, including the stories of the inventor/entrepreneurs behind penicillin and Post-it notes (pp. 8-9), are obiter dicta (i.e., ad hoc) that do not arise consistently *from within* the TAP equation.

One move they might be tempted to make in response would be to say that the parameters (*P* and the α_i*'s*) need not be set at fixed values but could be re-defined as a function of human action. But they cannot make this move because they need the parameters to be fixed at set values, so that the TAP equation will yield the characteristics of the hockey stick, including the initial long period of stagnation and the eventual "combinatorial explosion."

On pp. 5-10, Koppl et al. (2023) summarize "Competing Explanations of Technology." One of the subheadings is "Science, Culture, and Institutions" (p. 7). There they claim that institutions do not matter because they are "endogenous." But institutions are at least partly exogenous—for example citizens can choose to be responsible informed voters, or not. Much later, Koppl et al. (2023) substantially soften their position:

> . . ., we ignore the possibility that some desirable good becomes technologically possible but cannot find a market because of 'institutional' factors such as weak property rights. Such possibilities are quite real. Weak property rights in medieval China, for example, thwarted innovation (Lowery and Baumol 2013). Our model of niche evolution assumes a favorable institutional environment only as a first approximation that should be dropped when it is convenient to do so. (Koppl et al. 2023, p. 34)

But this is inconsistent with their earlier passage in which they rejected the possibility that institutions matter at all. And it will never be "convenient" for them to "drop" the assumption of "a favorable institutional environment" because bad enough institutions could reduce the parameters (*P* and the α_i*'s*) to zero, undermining the claim that the hockey stick, and the Industrial Revolution inflection point, are inevitable.

For me in the end, it does not matter so much whether they settle on the core version or the augmented version of the TAP model, because I worry that both versions ignore the innovative (Schumpeterian) entrepreneur.[3] Paraphrasing Joseph Schumpeter's own words (1940, p. 86), to give an account of capitalist economies with no mention of innovative entrepreneurs is like giving an account of Shakespeare's *Hamlet* with no mention of the Danish prince. Both the core and the augmented versions of the TAP model make no mention of the innovative entrepreneur.

2. **Does the TAP Equation Explain the Stylized Facts?**

Within economics a common explanatory method is to set out a few important empirical generalizations about the economy and then present an explanation that can explain them.[4] The more stylized facts that are explained by an explanation, the better the explanation. In our discussion so far, the main stylized fact has been the hockey stick of economic growth where the inflection point between the handle and the blade is the Industrial Revolution.[5] But to judge how well "Explaining Technology" explains technology more broadly, it is useful to see how well the paper explains a broader set of stylized facts, including but not limited to, the three stylized facts that are explicitly discussed in "Explaining Technology." In this section I discuss how well the paper explains 11 stylized facts about technology, starting with the three that the authors call "Our Tri-Data Result" (Koppl et al. 2023, p. 25).

Stylized Fact 1: The Hockey Stick of Economic Growth

The hockey stick graph of economic growth is Stylized Fact 1 (aka the first part of their "Tri-Data Result"). To evaluate the importance and soundness of the TAP model's explanation of Stylized Fact 1, a few questions must be answered. A first question is: how important is the hockey stick stylized fact? A second question is: how good an explanation of the hockey stick is the TAP model? A third question is: what alternative explanation might be better?

How important is the hockey stick stylized fact? The long horizontal handle shows for how many millennia so many *Homo sapiens* lived Hobbesian lives that were "poor, nasty, brutish, and short" (Hobbes 2006 [1651], p. 70). The inflection point, what Koppl et al. (2023) like to call "the combinatorial explosion," shows that something big happened, something unexpected—not just "unexpected," more like "impossible" or "inconceivable" if one's only tool for prediction was extrapolation. This inflection point is always labelled "the Industrial Revolution," a label that is not pure description but hides a partial explanation. The key description of the inflection point is that at that point, the lives of many ordinary people got noticeably, and soon substantially, better. The label "the Industrial Revolution" hints that the reason is that in England, and then elsewhere in Great Britain and Europe, and eventually widely, goods began to be produced in factories with new and improving technology.

The important message of this graph is the improvement in people's lives, but what makes the graph even more important is that it communicates its message in a visually compelling way. Most graphs dare us to extract an unambiguous message. This graph is refreshingly, dramatically clear. In my own account of the growth that started with the Industrial Revolution, I include a version of the hockey stick graph (Diamond 2019a, p. 38).

The hockey stick graph is important, but it does not express what is *most* important about the Industrial Revolution inflection point. The graph is usually presented with gross domestic product (GDP) as the dependent variable, mostly because we have procedures in place to measure GDP.[6] If you are one of the poor, then exponential growth of GDP promises to pull you out of poverty and into the middle class. But many intellectuals and many of those in the upper class and upper middle class now equate the growth of GDP with more "stuff" and increasingly express doubt that the pursuit of more "stuff" adds to happiness—countless books have been penned and read on downsizing and decluttering from too much "stuff." The declutterers view the hockey stick graph and shrug.

So although I include the graph in my *Openness to Creative Destruction* (2019) book, I devote many more pages arguing that the *most* important benefit from the growth of new technologies is in the breakthrough new goods that give us leaps in the length and quality of our lives—goods such as air conditioning, telephones, electric lights, airplanes, television, automobiles, elevators, antibiotics, and the internet (Diamond 2019, pp. 49-52). I make the case that these new goods are useful for almost all of the life plans that people choose, and especially for those life plans that seek the peak of the Maslovian hierarchy of fulfilment and creativity (Diamond 2019a, pp. 43-45). These breakthrough new goods, unfortunately, cannot be represented in so compelling a graph as the hockey stick of GDP. But we can ask readers to imagine what their lives would be like without them.

Having discussed the first question on the importance of the hockey stick graph we can turn to the second question on how well the TAP equation explains the hockey stick graph, especially the Industrial Revolution inflection point of the graph. In the core exposition of the TAP equation, *M* is "the number of distinct types of goods in the economy" (Koppl et al. 2023, p. 17). The core exposition proceeds to derive a hockey stick shaped graph with *M* on the y-axis, and "time" on the x-axis (Koppl et al. 2023, p. 17). For the TAP model to explain the hockey stick graph, it must at least imply the three key features of that graph: 1.) the initial very long period of stagnation, 2.) the final period of very rapid growth, and 3.) in between, but nearer the end than the beginning, the Industrial Revolution inflection point. We care most about the Industrial Revolution, so I will save that until last.

How does the model "explain" the very long initial period of stagnation? To answer that question requires some comments about the TAP equation. In the basic TAP equation (Koppl et al. 2023, p. 17, equation 1; reproduced below) *M* in period *t* is equal to *M* in period *t*-1 plus an expression that includes the parameters, *P* and the α_i's:

$$M_t = M_{t-1} + P\left(\sum_{i=1}^{M_{t-1}} \alpha_i \binom{M_{t-1}}{i}\right) \qquad (1)$$

Koppl et al. (2023) explain "we have a set of parameters, α_i ($i = 1, 2, 3, \ldots$), reflecting the portion of *i*-tuples of existing goods that are plausible candidates for combination or, in the case of $i = 1$, modification to produce a new good" (Koppl et al. 2023, p. 16).

Their *P* parameter is the probability "that a "plausible" combination will generate a new value-enhancing good in the current period" (p. 16). They approvingly quote (p. 15) Katherine Nelson and Richard R. Nelson as saying, "technology advances through processes that involve both trial and feedback learning, and conscious thought and calculation" (Nelson and Nelson 2002, p. 731) and then they immediately say, "Our model reflects this mix of insight and serendipity" (p. 15). But *then* they assume that both the α_i's and *P* are *fixed*. If insight depends on "trial and feedback learning, and conscious thought and calculation" won't insight vary based on what inventors and entrepreneurs choose to do, and what policies and institutions allow them to do? Serendipity is often associated with luck, but luck that is noticed and taken advantage of, so won't serendipity also vary based on what inventors and entrepreneurs choose to do, and what policies and institutions allow them to do? (Pasteur taught us that "chance favors only the prepared mind" (Pasteur 1854).)

And more broadly won't both the α_i's and P vary based on several factors including the extent of the rule of law, patents, and regulations, the size and flexibility of funding, the intelligence and perseverance of inventors and entrepreneurs, their access to scientific knowledge, and whether society provides them with dignity or hands them over to Stalin to be imprisoned or executed? Several of these factors can be influenced by the human agency of either inventors, entrepreneurs, policy makers, or citizens. By assuming these parameters are fixed, they are ruling human agency out of their model, not by observation or argument, but by assumption.

So at what values do they fix the parameters? They tell us that they fix the P at 0.0006 (p. 28). So out of 10,000 plausible combinations, only 6 will be turned into new value-enhancing goods? That seems very low. Did they run the simulations with other values? If so, what happened? And is there any argument or evidence that P should be about 0.0006, other than that it helps produce a good fit?

For the α_i's, they provide a formula that sets α_i as a function of i and two fixed parameters, θ and ρ (p. 29). They assign θ the fixed value of 6 and ρ the fixed value of 2 (p. 28). So using the formula and those parameter values, results in $\alpha_1 = 0.0278$, $\alpha_2 = 0.0069$, $\alpha_3 = 0.0031$, and $\alpha_4 = 0.0017$.

Then Koppl et al. (2023) parenthetically add "(In practice, we set α_i equal to 0 for $i > 4$.)" (p. 17).[7] **This amounts to assuming that no plausible combination can ever result from combining five or more goods.** This is clearly an unrealistic assumption since it is easy to think of many goods that consist of five or more component goods. For instance, in his famous essay, later mashed into a video riff by Milton Friedman, Leonard Read listed the *five* most basic components of a simple[8] pencil: cedar wood, paint, graphite, brass ferrule, and factice eraser (Read 1958).

Why then is the clearly unrealistic assumption made? Koppl et al. (2023) write that "We chose our parameters to ensure the model is coherent prior to 1 CE" (p. 27), suggesting that the parameters are selected so that the TAP equation will better fit the hockey stick. A longer explanation of the reason for this unrealistic assumption appears in a related paper by Steel, Hordijk, and Kauffman (2020) that Koppl et al. (2023) sometimes refer to in explaining the nuances and implications of their model. Steel et al. (2020) write: "Because in any simulation of the model the terms . . . quickly grow out of hand, we have chosen to put an upper limit K on how many goods can potentially be combined into new goods. For the sake of numerical simplicity, we have set $K = 4$" (Steel et al. 2020, p. 5).

Koppl et al. (2023) achieve the same restriction by setting α_i to 0 when $i > 4$. The reason for the restriction is even more fully explained in a recent paper by Cortês, Kauffman, Liddle, and Smolin (2025):

> *The TAP equation is in fact a family of equations, whose properties can to some extent be tuned* to best fit the circumstances in which it is being applied. To fully specify it requires us to choose the range of the index i of the combinatoric

term, the extinction rate μ, and either individual α_i for each term in the sum or a parametrized functional form that they can be derived from. *For most versions the generic behaviour is a flat plateau, followed after some time by a sharp super-exponential blow-up* (Koppl et al., 2018; Steel et al., 2020).

(Cortês et al. 2025, p. 9; *my* italics)

Cortês et al. (2025) are explaining that the parameters are chosen so that the version of the TAP equation reported will produce the features of the hockey stick graph. In the specific case of the α_i restrictions, M would "quickly grow out of hand" (Steel et al. 2020, p. 5) without the restrictions, which I take to mean that the model would no longer imply the extremely long initial period of stagnation before the Industrial Revolution. But that very long initial stagnation is a key feature of the hockey stick graph. To explain that key feature seems to require an ad hoc restriction to the TAP model, even though Koppl et al. (2023) claim that their model explains without "ad hoc elements" (p. 25).

The α_i's and P seem to be picked so that the equation fits the data and *not* picked on the basis of what values for them would be plausible, or (what would be even better) picked on the basis of empirical evidence on what the α_i's and P actually are. Koppl et al. (2023) claim "it is a strength of the model that we get a good fit even with such Spartan assumptions" (p. 16) and "our good fit is strong evidence in favor of the TAP model" (p. 30). This audacious claim implies that their model is strong because they get a good fit *in spite of* their simple and unrealistic assumptions, but in fact they get a good fit *because of* their simple and unrealistic assumptions—assumptions which are based, not on their independent truth, but on their ability to produce a good fit.

Some philosophy of science purists, like Karl Popper (1959), think that the only sound method in science is some version of commit-to-a-theory-and-then-test-it. This view suggests that it is a strength of a model when the model is created independent of the data and then in a later separate step, tested with the data.[9] A growing number of scientists are trying not just to advocate, but to seriously implement, this method by preregistering their hypotheses before they test them with analysis of the data (see, e.g., Nosek et al. 2018). But if the TAP equation is a curve-fitting exercise then it may at best be more of an elegant way to *summarize* the data, than a way to deeply or actionably *explain* the data. At worst it reminds us of the bed of Procrustes.

The second key feature of the hockey stick graph is the final period of very rapid growth. In discussions of the hockey stick graph, this last period is usually described as the period of exponential or near-exponential growth. Koppl et al. (2023) state that the TAP equation implies that growth in the final period will be "superexponential," and actually "infinite" (p. 21). They gamely try to make sense of this:

> Steel, Hordijk, and Kauffman (2020) show that the continuous-time version of the TAP process reaches infinity in finite time with probability one. The intuition is that over time more and more goods are produced within a given time slice such as a year or a day. At some point the rate of change becomes so great that the number of goods produced within a small time slice exceeds any finite number one might name. The TAP process is superexponential, and it has a singularity. We cannot somehow hit infinity in the real world. What would that mean? Thus, the singularity would be a regime change. It would mark the point at which our model

> no longer applies. We do not know whether a technological singularity, should it be coming, would be heaven, hell, or something else altogether. (Koppl et al. 2023, p. 21)

After the Industrial Revolution inflection point, the TAP model implies a period of continuous quickly accelerating "infinite" growth. Rather than admit this as a troubling false implication of their model, the authors declare a "regime change" where their "model no longer applies."[10]

The authors of "Explaining Technology" are not sure of the traits of the new regime they foresee but they expand on the "hell" possibility by saying we are already in "the crisis of the Anthropocene"[11] (p. 27). They even suggest that humans may act to achieve "degrowth" (p. 27) as a solution to the crisis.[12] In that scenario human agency would return to the world after the demise of the TAP equation, but more in the form of an environmental regulator than in the form of an innovative Schumpeterian entrepreneur.

The third and final key feature of the hockey stick graph, and the most important, is the Industrial Revolution inflection point. In the most common version of the hockey stick graph that has been used to understand the Industrial Revolution, the dependent variable (*Y*) of the graph is the output of the economy as measured by GDP (p. 26). Koppl et al. (2023) use an aggregate production function of GDP where the independent variables are *A* (knowledge), *L* (labor), and *K* (capital). Recall that in their initial exposition of the TAP equation *M* is "the number of distinct types of goods" (Koppl 35 al. 2023, p. 17). They connect this TAP equation with the aggregate production function by positing that *M* in the TAP equation is equal to *A* in the aggregate production function of GDP (p. 25). They proceed to show that the TAP equation implies the usual hockey stick diagram in terms of GDP (pp. 27-29).

I worry that it is false to claim that M is equal to A. New items in M come about by recombining goods in M to create some of the goods that are in the adjacent possible. Each new good in M is different from all the other goods in M, hence always increasing diversity. So Koppl et al. (2023) correctly claim that the TAP equation implies an increasing diversity of goods (pp. 1, 33, 38, and 42). But new knowledge can lead to greater GDP, *without* creating greater diversity. For instance, when the assembly line was devised, that knowledge was an increase in A, but not an increase in M (the diversity of goods). When Henry Ford applied knowledge of the assembly line to the production of standardized black Model Ts, he cranked out a lot of Model Ts, increasing GDP, but not increasing diversity.

Even today a firm can sometimes succeed by offering customers *less* diversity rather than more. When Steve Jobs returned to Apple the firm had "tons of products" (Phil Schiller as quoted in Isaacson 2011, p. 336) including 12 versions of the Mac (Isaacson 2011, p. 337), printers, servers, and the Newton personal digital assistant (Isaacson 2011, p. 338). One of Jobs's first actions was to cut Apple's diversity of product offerings back to only four, a laptop and a desktop personal computer (PC) for consumers, and a laptop and a desktop PC for professionals (Isaacson 2011, p. 337; Schlender and Tetzeli 2015, p. 225). The first-generation iMacs were a success at filling the consumer desktop PC quadrant.[13]

Another example confirms that greater knowledge (A) need not increase the diversity of goods (M). On trips I used to carry around a basic cell phone for calls, an iPod for music, and a camera for photos. New knowledge, created in part by Steve Jobs, Jony Ive, and their team, allowed the creation of the iPhone. Now I carry around one iPhone that combines the functions of all three previous devices (and more). If M is measured in terms of "distinct types of goods," this example would seem to indicate that even today M can become smaller and need not inevitably become larger as knowledge (A) increases.

A common complaint of the intelligentsia against the Industrial Revolution is that before the Industrial Revolution every table created by a craftsman was uniquely diverse, but that after the Industrial Revolution every table cranked out by a factory was similar to every other table. With mass production craftsmen "lost the ability to create unique pieces in response to varying needs" (Arnold and Smith 2005, p. 33). Note that part of this complaint is that with the Industrial Revolution diversity of goods *de*creased, not *in*creased. But for a poor family who lacked a table "it was better to have a table that looked like their neighbor's table than to have no table at all" (Diamond 2019, p. 63). The initial advantage of the Industrial Revolution was that it reduced costs, not that it always increased diversity.

Even if we concluded that the TAP model in some sense "explains" the hockey stick of economic growth, that would not necessarily imply that the TAP model is the best explanation. The third question with which we started this sub-section was whether there might be a better alternative explanation of the hockey stick of economic growth? Other explanations besides the TAP model might also explain the hockey stick graph, and might be closer to the truth, and more actionable by inventors, entrepreneurs, and policy makers. Imagine, for example, that the innovative

(Schumpeterian) entrepreneur does matter. Then an explanation that incorporates the innovative entrepreneur would have the advantage that it tells us what institutions and policies (less government regulation) would best enable the innovative entrepreneur to innovate. If action is possible and productive, then an explanation that is actionable is better than an explanation that implies that innovation is inevitable. And an actionable explanation that is not formal, can be a better explanation than a formal explanation that is not actionable.

Stylized Fact 2: The Number of Descendent Patents Citing an Earlier Patent Increase Rapidly (by a Power Law) Over Time

The patent citation Stylized Fact 2 (aka the second part of their "Tri-Data Result") is less momentous than the first one dealing with economic growth. The path of patent citations depends on many factors besides the growth of the adjacent possible, for instance changes in the legal requirements to cite previous patents, improvements in the technology for searching through past patents, and the number and experience of patent examiners. For example, examiners from the U.S. Patent Office often add many patent citations beyond those submitted by the patent applicant, adding about 40% of total patent citations (Alcácer et al. 2009, p. 420). The characteristics of the patent examiner can matter. For example, more experienced patent examiners tend to add *fewer* patent citations than less experienced patent examiners (Lemley and Sampat 2012, p. 817).

So is it coincidental, or proof of the power of the TAP model, that the model fits the patent citation data so closely? This result does not seem to have any implications for actions by inventors, or the design of institutions, or the policies of the government. And for the TAP equation to fit the data, the α_i parameters are again restricted to 0, for $i > 4$, which again seems ad hoc and arbitrary.

Stylized "Fact" 3: Increasing Complexity of Goods Over Time

In discussing Stylized Fact 3 (aka the third part of their "Tri-Data Result"), Koppl et al. (2023) say "the *complexity of goods will grow over time*" (p. 18, *their* italics) and explain that "'complexity' means number of component parts" (p. 18). Two questions are relevant: 1.) Does the TAP model imply increasing complexity? and 2.) Does the technosphere always exhibit increasing complexity? I have already noted (pp. 15-17 of this paper) that Koppl et al. (2023) set $\alpha_i = 0$ for all $i > 4$, which implies that no good can ever have more than four components. Given a straightforward interpretation, the TAP model does not imply increased complexity beyond four components.[14]

The second, more empirically interesting, question is whether, in the actual technosphere, complexity always increases monotonically over time. Although Koppl et al. (2023) express admiration of and debt toward Brian Arthur's research on technology (pp. 1-4, 7-8, 10-15, 21, 33, 35-36, and 55), Arthur may not support their claim of a monotonic increase in complexity. Channeling Thomas Kuhn's *The Structure of Scientific Revolutions* (2012 [1st ed. 1962]), Arthur writes that technologies become increasingly "elaborate" until they reach their "limits," at which point a new "principle" is found that is "simpler" (Arthur 2009, p. 157). When the new simpler principle is found and initially adopted, the new technology may have fewer component parts than the old, and hence represent a decline, not a growth, in complexity.

Koppl et al. (2023) write that they don't have good enough data to try any kind of systematic test. But they give as an example "the evolution from carriages to the modern automobile" (p. 18) and they briefly expand on automobiles as an anecdotal illustration that they believe is compatible with their claim (p. 33). But automobiles can also provide anecdotes *in*compatible with their claim. Paul David's classic "Dynamo" paper showed how the replacement of steam engines with electric engines in factories enabled the replacement of multi-story factories with "single-story, linear factory layouts" (David 1990, p. 358), making production simpler, most notably by making possible the horizontal assembly line famously exemplified by Henry Ford's manufacture of the Model T automobile.

A related automobile counter-example is that electric engines in automobiles are less complex than either internal combustion engines (ICE) or steam engines. The move from ICE automobiles to electric vehicles (EVs) is a move of ***decreasing*** complexity. This helps explain why EVs need less routine maintenance and why fewer firms supply EV parts than supplied ICE automobile parts (Veza et al. 2023, p. 461). An academic engineering paper comparing alternative ways of powering automobiles, including ICEs and EVs says that EVs "feature a simpler and more compact design than ICEs, with fewer moving parts and less complex transmissions" (Veza et al. 2023, p. 461).

Sometimes the development of computer technology has been toward greater simplicity, not greater complexity. Starting in the mid-1990s some PC processor chips were increasingly designed to perform functions previously performed by various auxiliary chips and other components, thereby reducing the total number of components in PCs. By 1999, "system on a chip" (SOC) integrated circuits had within them the functions of: "multiple processors, peripherals, communication subsystems, bus hierarchies, analog components, and radio frequency (RF)" (Rincon et al. 1999, p. 83). The development of SOC processors reduced the complexity of PCs, as measured by the number of separate components within the PCs.[15]

The development of computing technology provides other informative counter-examples. For instance, Steve Jobs and his lead designer Jony Ive were committed to simplicity, not diversity or complexity. Jobs's biographer Walter Isaacson describes the Power Mac G4 Cube that filled the professional desktop PC quadrant:

> The sophistication came from minimalism. No buttons marred the surface. There was no CD tray, just a subtle slot. And as with the original Macintosh, there was no fan. Pure Zen. "When you see something that's so thoughtful on the outside you say, 'Oh, wow, it must be really thoughtful on the inside,' " he told *Newsweek*. "We make progress by eliminating things, by removing the superfluous." (Isaacson 2011, p. 445; sentences in quotation marks are from Jobs; see also Segall 2012)

Jony Ive was Steve Jobs's design collaborator during the years when Apple released some of its most successful new products, such as the iPod, the iPhone, and the iPad. For Ive "keeping things simple was the overall design philosophy" (Kahney 2013, p.

x). Speaking specifically of the design of the Power Mac G5, Ive said: "We kept going back to the beginning again and again. Do we need that part? . . . It became an exercise to reduce and reduce, but it makes it easier to build and easier for people to work with" (Ive as quoted by Kahney 2013, p. x).

In designing the iPod Jobs's "main demand was 'Simplify!'" (Isaacson 2010, p. 388). He showed he was serious and "astonished his colleagues" when he eliminated the on-off button (Isaacson 2010, p. 389), deciding that the iPod would go dormant when not in use, but come alive when a key was touched, making it quicker and simpler to use and sleeker to see. The on-off switch stayed gone on the iPhone as well. In 2007 an Apple team was brainstorming the development of a new notebook computer when Ive asked if they could simplify by eliminating the keyboard and replacing it with a virtual keyboard on the display screen—so the team pivoted to develop a tablet computer that became the iPad (Isaacson 2010, p. 337).

Elon Musk's life mission is to bring humans to Mars (Isaacson 2023, p. 92). A main constraint is the quantity of fuel needed to go the distance, a quantity that depends on the weight of the rocket. So Musk is driven to reduce weight by simplifying the rocket, eliminating components whenever possible:

> Like a mountain climber paring the contents of his knapsack, Musk obsessed over reducing the weight of his rockets. That has a multiplier effect: removing a bit of weight—by deleting a part, using a lighter material, making simpler welds—results in less fuel needed, which further reduces the mass the engines have to lift. When he walked through SpaceX's assembly lines, Musk would pause at each station, stare silently, and challenge the team to delete or trim

> some part. At almost every encounter, he maniacally hammered home the message: "A fully reusable rocket is the difference between being a single-planet civilization and being a multiplanet one." (Isaacson 2023, p. 227; see also p. 478)

Besides the above three stylized facts, together labelled the "Tri-Data Result" in "Explaining Technology," we should also examine whether some other important stylized technology facts can be explained by the TAP model. I examine some of those below.

Stylized "Fact" 4: Accelerating Arrival of the Next New Thing

In his 2023 TED talk Kauffman says that 50,000 years ago not many new things came into existence within any 83-year period, but that in the 83 years of his life (as of 2023), he has seen a great many new things come into existence (Kauffman 2023, at about 08:36). Then he goes on to say: "The TAP process has the following property. Every time you make something new, the waiting time for the next new thing is cut in half. A thousand years, 500 years, 250, a year, six months, three months, we're going to get a great acceleration" (Kauffman 2023, at about 09:59). Although stated less colorfully, Koppl et al. (2023) agree with Kauffman (2023):

> Cortês et al. (2022) show that with each addition of an item in a TAP process, "it must then take no more than half as many steps to add the next, then half

again for another, and so on." Change speeds up over time. (Koppl et al. 2023, p. 21)

However stated, the important question is whether the TAP equation's implication of continuous acceleration is actually true? Or put differently, is this stylized fact actually a fact?[16]

In recent decades some economists and technology observers have complained that instead of experiencing technology *ac*celeration, we are experiencing technology *de*celeration. For instance, Tyler Cowen (2011) and Larry Summers (2015; see also Eggertsson et al. 2016) believed we were in a period of economic secular stagnation. Cowen famously claimed that we had picked all the low-hanging technology fruit (his version of the adjacent possible?). Several other credible observers of technology are agreed that the rate of technological innovation is decreasing (Gordon 2016; Park et al. 2023; Smil 2023a and 2023b; Wu et al. 2019).[17]

Stylized Fact 5: Cases of Technology Reversal

In the version of the TAP equation presented in "Explaining Technology," once a technology appears, it never disappears. But in related combinatorial accounts, technologies are allowed to disappear (Arthur 2009; Cortês et al. 2025). In Arthur's account an old technology can disappear if a new technology does a better job of meeting human needs (Arthur 2009, pp. 157 and 194-195). In the formal account of Cortês et al. (2025), less explanation is provided of their "extinction rate of existing objects" (p. 1), but they do parenthetically attribute it to "extinction or obsolescence" (p. 1), suggesting an underlying account similar to Arthur's.[18] A more serious loss, what I call a "reversal," would occur if a technology disappears without being replaced by a newer and better technology. Neither Koppl et al. (2023) nor the related accounts provide an explanation for such reversals.

But some such reversals have indeed occurred. Some of these would be local, as when Tasmanians lost their ability to build boats (Ridley 2010, pp. 77-79). Matt Ridley attributes this reversal to a small population that had become cutoff from the larger population in Australia by rising seas. A more widespread reversal was the disappearance in the early Middle Ages of the ability to make the high-quality concrete that had been widely made by the Romans, concrete that lasted much longer and was more self-healing than modern concrete. Only recently, through a reverse engineering of samples of ancient Roman concrete, have we begun to again understand how to make concrete closer to Roman quality (Zeeberg 2024; Seymour et al. 2023). Widespread loss of a still-highly-useful technology does not seem compatible with any version of the TAP model.[19]

Stylized Fact 6: Technological Advance in Recent Decades Has Been Less Bold Than Previously

Peter Thiel (Thiel and Masters 2014, p. 9) and David Graeber (2012), argued that the breakthrough new goods that had been promised to the children of the 1950s through 1980s, for instance flying cars, have not been created and brought to market. Many years ago Thiel famously said "We wanted flying cars, instead we got 140 characters" (as quoted in Lewis-Kraus 2024)[20] referring to the original character limit for Tweets on Twitter. Graeber put it this way:

> Where, . . ., are the flying cars? Where are the force fields, tractor beams, teleportation pods, antigravity sleds, tricorders, immortality drugs, colonies on Mars, and all the other technological wonders any child growing up in the mid-to-late twentieth century assumed would exist by now? (Graeber 2012)

Thiel and Graeber are not mainly complaining that we are getting fewer new goods but instead are complaining that the new goods we are getting are not the impressive new goods that we had hoped for, what I call the breakthrough new goods. Peter Thiel also complains that technology is only advancing narrowly, in the area of AI (Thiel as quoted in Douthat 2025, p. 9).

The TAP model says nothing about whether the new good that results in an increase in M is Joy Mangano's Miracle Mop that can clean the floor a bit better, or Elon Musk's SpaceX rocket that can get us to Mars. The mop and the rocket count equally in the TAP equation. Koppl et al. (2023) aim at "Explaining Technology." Part of what we want from an explanation of technology, are answers to these two questions. What drives whether technology advances broadly or narrowly? What drives whether technology advances in a timid increment (the mop) or a bold leap (the rocket)?

Stylized Fact 7: In the Year 1000, *M* Was Larger in China, But England Achieved the Industrial Revolution Inflection Point First

Over several decades of research Joseph Needham collected and published in multiple volumes, the many early advances in science and technology that occurred in China (see Winchester 2009). In the year 1000 China was more technologically advanced (Landes 2006, p. 3) and had a much larger population than England. The combinatorial adjacencies in the year 1000 were more numerous in China than in England, so the TAP model would seem to predict that China should have been the initial location of the Industrial Revolution inflection point. So why did the Industrial Revolution happen first in England instead of China? (See Landes 2006; Wootton 2015, p. 19.)

The TAP model has no answer, but some competing explanations of technology are not so silent. Justin Yifu Lin, for instance, argued that China's bureaucratic institutions created incentives and constraints that discouraged entrepreneurship (Lin 1995). The surest path to prestige and income in early China was the civil service whose members were selected on the basis of difficult and competitive civil service exams. Ambitious citizens spent their time studying for the exams rather than gaining the skills and experiences that enable success in invention and entrepreneurship (Lin 1995, pp. 284-285).

Douglass North argued extensively, and persuaded many, that the development of the institution of property rights in England was key to the Industrial Revolution first occurring in England (North 1981, pp. 164-165). Deirdre McCloskey summarized and critiqued over 25 alternative explanations of the Industrial Revolution (including

North's), concluding that the key was that the English accorded respect ("dignity") to the merchant and the entrepreneur (McCloskey 2010).

My own view is that multiple causes jointly explain the Industrial Revolution (Diamond 2012b, p. 202; see also Diamond 2019a), including institutions and policies that support rule of law, property rights (including patents), limited regulations, low taxes, and respect for inventors and entrepreneurs. The main point is that even though there is not a consensus on this important issue, there are plausible explanations—but the TAP model is not one of them.

Koppl et al. (2023) admit that consistent with their TAP model, "takeoff might have occurred in another time or place" (p. 24) and that the time or place is mainly determined by a "stochastic process" (p. 24) aka "chance" (p. 25). But they do *not* admit that any of the alternative accounts that the TAP model "*deflates*" (Koppl et al. 2023, p. 24; *their* italics) might do much better. They say that the alternative accounts can at most only explain to "some degree the timing and location of takeoff" (p. 24).

In other words, they are implying that the TAP model should not be faulted for failing to explain that the Industrial Revolution inflection first occurred in England. But remember that the title of their paper is "Explaining Technology," and not just "Explaining the General Shape of the Hockey Stick Graph." The TAP model aspires to be "an explanation of technology" that "has certain advantages over currently available rivals" (p. 11). If Koppl et al. (2023) are "Explaining Technology" isn't this stylized fact puzzling enough and important enough for us to expect an explanation? If we want technology to advance, then we want to know why it advances more at some times and in some places than at other times and in other places. We want an explanation, for instance, that tells us whether rule of law, property rights, and low regulatory burden, matter.

Stylized Fact 8: In 1700s and 1800s, Britain Led France in Technology

In the 1700s and 1800s France had a larger population and equal or better science, but Britain led in the development of industrial technology, and perhaps not coincidentally, in GDP per capita (Rosen 2010, p. 266). Presumably the adjacencies at the start of the period were similar in Britain and France, so the TAP model cannot explain why technological innovation was greater in Britain. But that does not imply that the difference is inexplicable.

William Rosen's explanation is that Britain honored its inventors more than France did, and through its patent system had developed a better institution for providing less schooled citizens the means to invent (Rosen 2010, pp. 267-270). David Landes pondered:

> "why France has so often failed to appreciate its own inventors. From Lebon's discovery of gas lighting at the turn of the eighteenth century, through Girard's spinning machine, Sauvage's screw propellor, and Verguin's accomplishments in artificial dyes, to Tellier's refrigerator and beyond, the list of innovations which originated in France only to find their quickest and greatest development abroad is quite impressive." (Landes 1949, p. 51)

President George W. Bush was once unfairly ridiculed for allegedly saying "The problem with the French is that they don't have a word for entrepreneur" (Diamond

2006). The ridicule is unfair both because of the absence of evidence that Bush ever said it, and because if he *had* said it, he would have had a point. Just because a Frenchman originated the word does not imply that his countrymen have made good use of it.

Stylized Fact 9: The Stagnation of Technology in the U.S.S.R. under Stalin

Technology writer Kevin Kelly, the author notably of *What Technology Wants* (2010) and *The Inevitable* (2016), reveals the implications of the claim that technological progress is inevitable, and in doing so unintentionally makes a kind of *reductio ad absurdum* argument against the claim. Kelly endorses (2010, p. 45; 2016, pp. 193 and 209) the combinatorial theory of Brian Arthur, which Koppl et al. (2023), acknowledge as providing an important foundation for their TAP (Koppl et al. 2023, pp. 1 and 12). Kelly goes on to boldly embrace what other combinatorialists do not always openly admit—that their explanation of technological progress implies that it is inevitable, unaffected by the perseverance of entrepreneurs or the oppression of tyrants.

Kelly writes that: “If, in a counterfactual history, communism had won the cold war, and microelectronics were invented in a global Soviet style society, my guess is that even that alternative policy could not stifle Moore’s Law” (Kelly 2009; see also Kelly 2010, pp. 159-168). Kelly’s guess is hard to affirm. Pagan Kennedy in *Inventology* points out that the imprisoning and killing of inventors under Stalin substantially slowed the advance of technology in the U.S.S.R., as measured, for instance, by the number of patents filed (Kennedy 2016, pp. 195-196; Graham 2017, p. A17; Ings 2017; for post-Stalin evidence, see Stausbaugh 2024).

Much has been written about the exemplary inventiveness, entrepreneurship, and management at Intel (e.g., Berlin 2005; Grove 1995, 1999; Isaacson 2014; Malone 2014; Tedlow 2007; Thackray et al. 2015). The human agency of Andy Grove, Robert Noyce, Gordon Moore himself, and several of their successors, mattered in making Moore's Law true for so many decades. Moore's Law remained true for those decades, not because it was inevitable, but because exemplary inventors, entrepreneurs, and managers worked very hard and very effectively to *make* it true.

But this is not the strongest evidence. The strongest evidence against the inevitability thesis comes from reading the biographies of breakthrough inventors and innovative entrepreneurs, which we will briefly sample in a future section of the paper. Were they all delusional when they thought they were mightily struggling to create new products and bring them to the market?

Stylized Fact 10: Technological Advance Is Greater in South Korea Than in North Korea Even Though Before 1945 They Shared the Same Culture, History, and Adjacencies

Bart Wilson points out that Koppl et al. (2023) cannot explain the dramatic superiority of South Korea over North Korea in technology and GDP in the years since the division of Korea in 1945 (Wilson 2025, pp. 3-4). For a compelling visual illustration of the dramatic superiority of South Koren technology and GDP, view a photo that shows the brightness of the night sky in South Korea compared to the darkness of the night sky in North Korea (Henderson et al. 2012, p. 1002).

An accident of history created a natural experiment where much was held constant, including initial language, history, culture, and technological adjacencies. Although the canonical paper of Koppl et al. (2023) is entitled "Explaining Technology," it cannot explain why technology and GDP in South Korea grew while in North Korea they stagnated. But that does not mean that the difference is stochastic or inexplicable. The difference can be explained by accounts that emphasize that technology will flourish where institutions and policies support rule of law, property rights (including patents), limited regulations, low taxes, and respect for inventors and entrepreneurs.

Stylized Fact 11: Technological Advance Is Greater in the U.S. Than in Europe Even Though Europe Has More Population and the Same Adjacencies

In recent decades technological dynamism has been greater in the U.S. than in Europe (Luhnow and Fairless 2025; Kitsantonis 2025; Satariano and Smialek 2025; Sternberg 2025). To measure technological dynamism, Koppl et al. (2023) suggest that "patents give us a record of innovations, albeit an incomplete one" (p. 30). In spite of Europe's population advantage, the number of patent applications to the European Patent Office (E.P.O.) in 2024 was about 199 thousand while the number of patent applications to the United States Patent and Trademark Office (U.S.P.T.O.) in FY2024 was *three times as many* (about 601 thousand). In addition, U.S. applicants filed 24% of the applications to the E.P.O.[21]

The U.S. had substantially more patent applications than Europe, even though the population of Europe was larger than the population of the U.S. (In 2024 the population of the European Union (E.U.) was about 449 million and the population of the U.S. was about 336 million.)[22]

Amar Bhidé has persuasively argued that technological inventions flow easily across borders so that technologies that are invented in one country are soon available in other countries (Bhidé 2008, pp. 14-15). So presumably Europe and the U.S. have roughly the same number of adjacencies. Based on the TAP model, wouldn't we then expect that Europe, with its greater population, would at least equal, if not exceed, the U.S. in technology advance?

What does not flow so easily across borders is the entrepreneurship needed to successfully bring new technologies to market (Bhidé 2008, pp. 15-16). According to my alternative explanation of technology, technology will flourish where entrepreneurship is enabled by institutions and policies that support rule of law, property rights (including patents), limited regulations, low taxes, and respect for inventors and entrepreneurs.

3. **Breakthrough Inventors and Innovative Entrepreneurs**

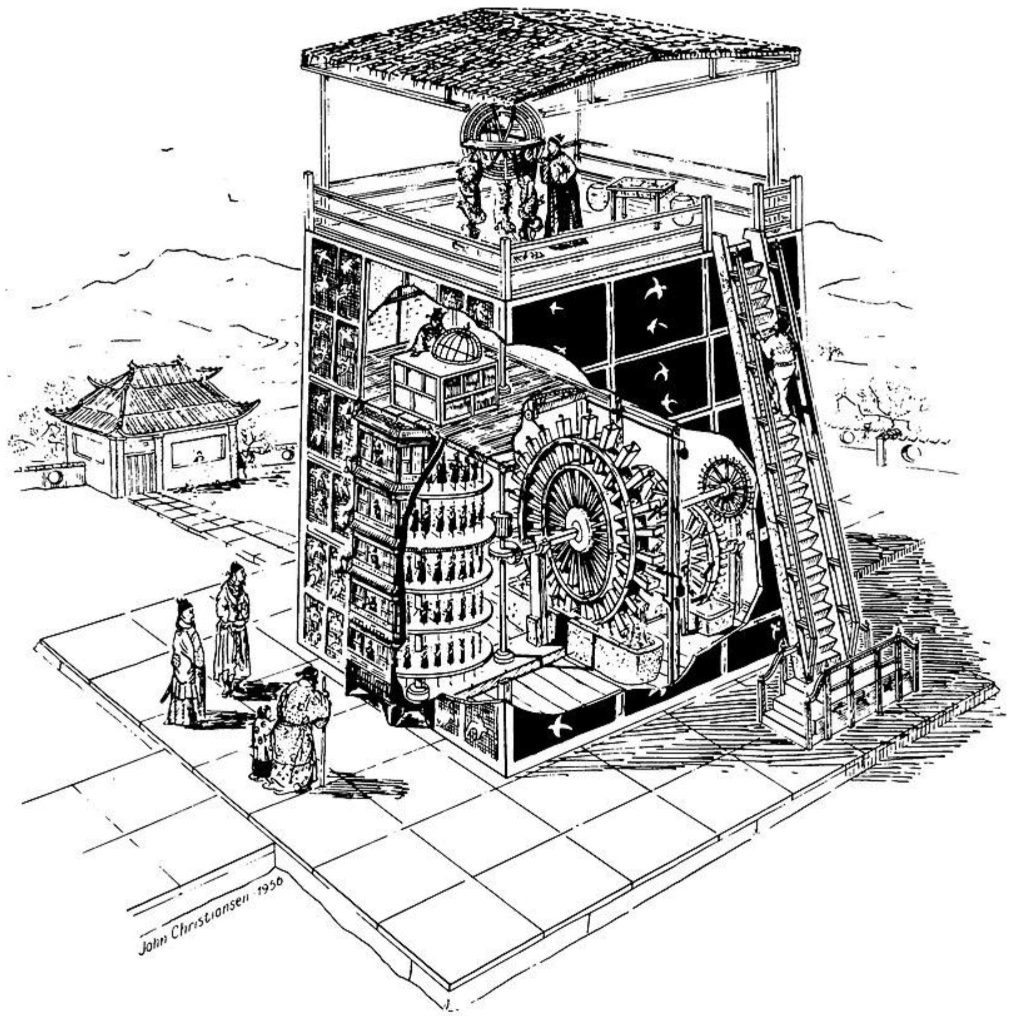
Clarity requires that "invention" be distinguished from "innovation" and that "inventor" be distinguished from "entrepreneur" (Schumpeter 1947, p. 152; 1950

[1942], p. 132; see also Diamond 2019a, p. 5).[23] "Invention" is the process of solving the technical problems to initially create a new good. "Innovation" is the overcoming of a variety of obstacles (e.g. manufacturing, transportation, marketing, regulatory) in order to successfully bring the new good to market with good enough features, quality, and price, so that consumers are willing to buy it, and so that revenues exceed costs. The inventor invents; the entrepreneur innovates.

Koppl et al. (2023) do not distinguish between the inventor and the entrepreneur. Their preferred term is "tinkerer" who they equate with both "invento" and "Kirznerian entrepreneur." Recall that their M is "the number of distinct types of goods in the economy" (p. 17). They apparently falsely believe that once a new type of good is tinkered together it is automatically "in the economy." Counter examples inc lue the inventors Frank Hursey, Moses Farmer, and John Fitch.

Frank Hursey will be discussed in more detail later in this section. Suffice it to say here that Hursey invented QuikClot to stanch severe bleeding but was discouraged and had given up when he could not interest major companies to make and sell his invention. If innovative entrepreneur Bart Gullong had never signed on, QuikClot would never have been "in the market." Moses Farmer invented a battery-powered system of electric lighting that he used to light his home for several years, and then abandoned (Diamond 2019a, p. 5). It took the entrepreneurial side of Thomas Edison to not only invent, but also successfully bring to market, his alternative system of electric lighting. Inventor John Fitch invented a steamboat that even operated for a summer on the Delaware River (Flexner 1944). Lacking strong patent protection, Fitch was unable to raise the funds he needed to keep his steamboat "in the market." The entrepreneurial side of Robert Fulton later overcame this and other obstacles which is why we now remember him, and not Fitch, as the "inventor" of the steamboat.

For a good to count as part of the M, it is not enough that some inventor invents it but no one ever brings it to market. Someone needs not only to invent a working prototype, but also to make it in a way that it is cheap enough, with the right mix of features, that consumers are willing to buy it at a price that is greater than its cost of production. These latter tasks are the jobs of the innovative entrepreneur. For further illustration consider the drawing below.



Clock tower built by engineer Su Song, completed in 1094, presented to the Emperor Zhezong of Song, and dismantled by invaders in 1127 who hauled it to their capital in Beijing but could not put it back together. (Source of drawing: https://en.wikipedia.org/wiki/Su_Song#/media/File:Bulletin_-_United_States_National_Museum_(1959)_(20481431946).jpg)

The drawing above is of a clock made for a Chinese emperor. The clock was a complex piece of technology, made of many components. But few besides the emperor ever saw it. An invading army dismantled it and hauled the components to their capital in Beijing but could not figure out how to put them back together. The Chinese society did not encourage or enable innovative entrepreneurs to bring such new technologies to the people. Culture and institutions can matter. So it is not enough for an inventor to put the components together to create a new good. Innovative entrepreneurs are needed, and also a society in which innovative entrepreneurs are encouraged, or at least allowed, to act.

In the augmented version of the TAP model, the human agents of technological progress are usually called tinkerers, but sometimes also Kirznerian entrepreneurs. Koppl et al. (2023) seem to sometimes be conflicted on the characteristics of successful tinkerers. On p. 16 they say that the plausibility of a combination depends partly on foresight and intelligence and illustrate by saying that the Wright brothers "did not try to combine locomotives, ink pots, and mustard seeds." But on p. 54 they say: "Technological change is not so much the product of reason, intelligence, and foresight as of tinkering and improvisation." In the first passage foresight and intelligence are *part of* tinkering, while in the second passage intelligence and foresight are *contrasted with* tinkering. How do we find out which is right? The answer is less likely to come from more clever modeling, but rather from deep empirical dives into what breakthrough inventors and innovative entrepreneurs think and do when they are inventing and innovating.

A rich array of biographies, autobiographies, and histories of inventions and innovations can be mined for insights about how inventors and innovative entrepreneurs think and act. In the rest of this paper, I will describe the goals, methods, and achievements of a variety of inventors and entrepreneurs, including William Coley, Bart Gullong, Frank Hursey, Jony Ive, Steve Jobs, Elon Musk, George Stephenson, Leo Szilard, Peter Thiel, Josiah Wedgwood, and Wilbur Wright. With more space and time, existing sources could be usefully studied on many others, including John Fitch (Flexner 1944), Guglielmo Marconi (Weightman 2003), John D. Rockefeller (Chernow 1998), Frederic Tudor (Weightman 2003), and Cornelius Vanderbilt (Stiles 2009).

Breakthrough inventors and innovative entrepreneurs differ from each other in many ways. But one way in which they are the same: what they did was not easy. It was not spontaneous, emergent, and inevitable; they had a goal and they could have given up. They needed to do a lot more than simply "open one of those doors and *stroll* into that room" (Johnson 2010, p. 31, *my* italics). In the rest of this section, I will outline several such cases, which provide evidence bearing on the claims of the TAP model.

Josiah Wedgwood near the start of the Industrial Revolution, in the mid to late 1700s, through systematic, documented, science-informed experimenting (not just improvised jury-rigging) devised new and better recipes for making a variety of better pottery (Hunt 2021, pp. 38, 159-161, 183, and 199-201). But for his better pottery to be marketable, a key component was less bumpy transportation, so his pottery wouldn't break (Hunt 2021, pp. 51 and 63). Wedgwood was acutely aware of this problem since in 1762 the dangerous condition of the roads caused an accident that seriously injured his right knee, already weakened from smallpox, and that resulted in the amputation of his leg (Hunt 2021, pp. 51 and 78-79). So marketable-better-pottery was not yet part of the adjacent possible. Did he give up? No, he became an advocate and subscriber to raise funds for a new road (pp. 34 and 45-46) and starting in the mid-1760s signed on as an advocate and eventually as Treasurer for the creation of the Trent and Mersey Canal (p. 69).

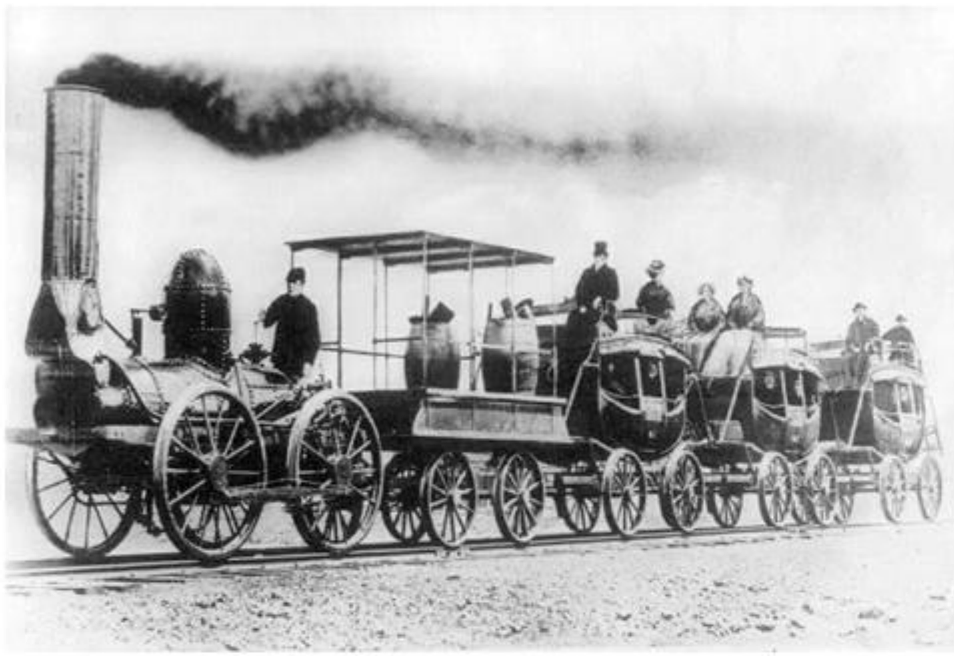


Figure 2 The image shows the DeWitt Clinton locomotive pulling coaches on the Mohawk & Hudson Railroad. The image was published in the Scientific American in 1920 (Unattributed 1920).

(The proximate source of the above photo is Koppl et al. 2023, p. 16.)

Joseph Schumpeter once claimed: "add successively as many mail coaches as you please, you will never get a railway thereby" (Schumpeter 1961, p. 64, fn. 1). As if to refute Schumpeter, Koppl et al. (2023) reprint the photo above of an early locomotive pulling early train coaches. Our attention is immediately drawn to the three coaches at the end of the little train. They look just like the horse-drawn stagecoaches we see in cowboy movies of the settlement of the West, providing compelling visual evidence that even the major innovation of the railroad just involved minor jury-rigs of what already existed. Or do they? We should move our eyes to the left in the photo and settle them upon the locomotive. That was the key innovation of the railroad, the "motive power."[24] And that was not a mere jury-rig of what already existed.

George Stephenson was the inventor and entrepreneur most responsible for the existence of the locomotive (Rosen 2010, p. xiii). Stephenson was born to a dirt-poor illiterate miner and his wife, in 1781 (Smiles 1879, pp. 13-14). He received no schooling and started working in the mines at a young age (Smiles 1879, p. 18). By the time he was about 17 he was a "plugman," assigned to keep a tube plugged, as required for a mine pump to work (Smiles 1879, p. 22). Samuel Smiles reports that Stephenson:

> applied himself so assiduously and so successfully to the study of the engine and its gearing—taking the machine to pieces in his leisure hours for the purpose of cleaning and understanding its various parts—that he soon acquired a thorough practical knowledge of its construction and mode of working, and very rarely needed to call the engineer of the colliery to his aid. His engine became a sort of pet with him, and he was never wearied of watching and inspecting it with admiration. (Smiles 1879, p. 22).

From his meager wages he paid for night lessons "in spelling and reading" and "at the age of nineteen he was proud to be able to write his own name" (Smiles 1879, p. 24). He quickly worked his way from job to job, each one with greater responsibility and pay, and increasing involvement with engines, running them, maintaining them, repairing them, and eventually improving them. Stephenson was entranced by the simple Newcomen pumps that drew water from the mines. This part of his account might seem compatible with the stochastic tinkering account of "Explaining Technology." But even here Stephenson's improvements involved less stochastic combining, and more purposeful plausible modifying.

Stephenson's first locomotive, the Blucher, was built in 1814, designed for coal-hauling. The Blucher "was a giant step toward practical steam locomotion" (Rosen 2010, p. 301), incorporating an early blastpipe, which increased the power of the locomotive. In a couple of years Stephenson included important improvements in the wheels, suspension, and especially in how the pieces of track connected with each other (Rosen 2010, p. 301). A powerful reliable locomotive was of little use without strong, durable, cheap-enough track on which to run the locomotive. Track was an important complement to locomotives. (Kauffman (2019, pp. 129-139) emphasizes the importance of product complements.) Eventually Stephenson went on to achieve other innovations, most notably in his Rocket locomotive, that won a competition for performance and reliability, making it the "most famous locomotive ever built" because it arguably "ushered in the age of steam locomotion" (Rosen 2010, p. xiii).

How did he achieve these innovations? Trial and error was part of it, but not in the tinkering sense of random jury-rigs. Stephenson's prior experiences put him in a position to know what might work and what was unlikely to work. A lot of this knowledge would have been tacit, unarticulated. Melanie Mitchell, a thoughtful skeptic of claims for AI's generative intelligence, suggested to Russ Roberts that our unarticulated knowledge may be a far greater part of our total knowledge than we understand or appreciate.[25] Cognitive psychologist Gary Klein agrees and represents the unarticulated as the below-water part of the iceberg of human knowledge (Klein 2023).

Smiles describes Stephenson as having curiosity and a deep and broad understanding based on his reading and especially his experience. But he often was not able to articulate what he correctly understood. This sort of knowledge is often described as "intuition." Smiles says that Stephenson's:

> familiar acquaintance with the steam-engine proved of great value to him. His shrewd insight, and his intimate practical acquaintance with its mechanism, enabled him to apprehend, as if by intuition, its most abstruse and difficult combinations. The practical study which he had given to it when a workman, and the patient manner in which he had groped his way through all the details of the machine, gave him the power of a master in dealing with it as applied to colliery purposes. (Smiles 1879, p. 62)

But this "intuition" should not be thought of in some inborn or mystical sense; it is knowledge based on patterns observed from experience but not, or at least not yet, articulated.[26]

In his later adulthood Stephenson became more of an entrepreneur and less of an inventor, although he always combined elements of both—even early-on when he was mainly an inventor, he invented with an eye toward what would make his invention commercially viable. When he was on the path to the Rocket, some of his friends wanted him to apply his ideas to develop a steam vehicle that would run on regular roads. But he did the calculations to show that the power from early locomotives would not be enough to overcome the resistance of existing low-quality roads, so he stuck to locomotives on rails that provide less resistance than roads, and whose quality he innovated to improve (Smiles 1879, p. 114). He had a vision[27] of what a train could be and knew that to achieve it he not only had to achieve good-enough motive power, but also good-enough tracks and rights-of-way—items that were not just "lying around" adjacently waiting to be combined into a railroad. Stephenson had to actively do a lot to make it happen, first mostly as an inventor and then mostly as an entrepreneur.

Edward Pease was another dedicated entrepreneur (Smiles calls him a "projector" (p. 123) planning to build a "tramroad" with horse-drawn carts on tracks (Smiles 1879, pp. 126-127). Stephenson went to see Pease and startled him by saying that he could make locomotives work better than 50 horses (Smiles 1879, p. 127). Pease took a chance, enabling Smiles to create the first passenger railroad on the planet, the Stockton and Darlington.

The experience that Stephenson acquired building embankments for the Stockton and Darlington may have proven useful to him later when he signed on as the chief engineer in the building of the Liverpool and Manchester Railroad. The route required laying track over an extensive bog called "Chat Moss." In testimony before a committee of Parliament, those opposed to the railroad

> mainly relied upon the evidence of the leading engineers—not like Stephenson, self-taught men, but regular professionals. One of these, Mr. Francis Giles, C.E., had been twenty-two years an engineer, and could speak with some authority. His testimony was mainly directed to the utter impossibility of forming a railway over Chat Moss. *"No engineer in his senses,"* said he, "would go through Chat Moss if he wanted to make a railroad from Liverpool

> to Manchester. . . . In my judgment *a railroad certainly cannot be safely made over Chat Moss without going to the bottom of the Moss.* (Smiles 1879, pp. 167-168; Smiles's ellipses and italics)

Local residents of the Chat Moss area also predicted failure, and at one point they seemed to be right.

Culverts were installed to drain water from the bog along the course of the intended embankment, but often "the drains filled up almost as quickly as they were dug" (Williams 1883, p. 132; see also Smiles 1879, p. 171). Where the bog was dryer and firmer, they would "spread branches of trees and hedge-cuttings" on top, but where it was wetter and softer, Stephenson had workers "transversely" place four feet by nine feet "hurdles" along the path of the embankment (Smiles 1879, pp. 177-178; see also Williams 1883, p. 133). Neither Smiles nor Williams define "hurdle" in this context but the *O.E.D.* definition that seems appropriate is: "a portable rectangular frame that has horizontal bars that are interwoven . . . with . . . hazel, willow, etc." flexible branches (*O.E.D.* 1971, p. 464).

Samuel Smiles says "Such was George Stephenson's idea in contriving his floating road—something like an elongated raft across the Moss; and . . . he steadily kept it in view in carrying the work into execution" (Smiles 1879, p. 177; my ellipsis). "A thin layer of gravel" was spread on top of the "raft" except where the bog was especially soft, in which case "cakes of dry turf or bundles of heath" would be substituted for the gravel (Smiles 1879, p. 178). Special challenges arose at the Manchester side of the edge of the bog, where whatever was placed to build up the embankment, soon sank into the bog. For several weeks, Stephenson had workers skim moss and peat from the surrounding bog, which were then dried, and used to fill-in the embankment, but to no visible effect (Smiles 1879, pp. 179-181).

What they filled in kept sinking. The workers, the directors of the railroad, almost everyone except Stephenson began to despair. Smiles reports:

> In the midst of all these alarms and prophecies of failure, Stephenson never lost heart, but held to his purpose. His motto was "Persevere!" "You must go on filling in," he said; "there is no other help for it. The stuff emptied in is doing its work out of sight, and if you will but have patience, it will soon begin to show." (Smiles 1879, p. 180)

Finally the embankment began to rise. The embankment over Chat Moss was a key component of the Liverpool and Manchester. It was created by George Stephenson against the odds and against the experts.

What Stephenson used to build the embankment over Chat Moss was in a sense "just lying around," but that belies the hard task: what among all that is lying around will be useful, and how do you combine which components, to make the embankment? Teppo Felin and Madison Singel understand the problem: "the set of potential combinations is astronomically large, raising the question of how humans somehow arrive at useful combinations (amongst indefinite possibilities)" (Felin and Singel 2026, p. 1). Their answer is that "combinatorial salience" is generated from theory.

That happens, but is certainly not the full story, and may not even be the *main* story. Many exemplars of breakthrough inventors and innovative entrepreneurs are not masters of theory but *are* masters of informal knowledge (Diamond 2019a, pp. 23-34). Our current exemplar, George Stephenson, was not well-versed or articulate about theory,[28] but had a rich reservoir of experience from which he had derived actionable patterns, and from which he could simulate what might happen if he tried something new within the domain of his experience.

To fill this reservoir took a lot of time, effort, and curiosity (Pasteur's prepared mind). How did he make the leap from the reservoir to the new? In the future we should try to understand better how he made the leap from the reservoir to the new, so that we can encourage such leaps in ourselves and others. Gary Klein has made a credible early effort in his *Sources of Power* (2017) and *Seeing What Others Don't* (2013).

For the railroad to exist required more than just the invention of a powerful enough and reliable enough locomotive. It also required strong enough tracks, and stable enough, straight enough, and level enough rights-of-way for the tracks to be laid. And it required laying tracks over, under, or around obstacles like Chat Moss. Stephenson made major contributions to these issues as well, often more in the role of an entrepreneur than an inventor. As an entrepreneur he also set up the first locomotive factory.

Many miners died from gas explosions; Stephenson's own father was blinded by a mine accident that may have been an explosion. So maybe it was personal when Stephenson invented a lamp that would not set off an explosion when it came in contact with gas. He designed it so that air entered and exited the lamp through small holes. It turns out that flames do not easily pass through small holes, at least when the holes are in material that can dissipate heat. Stephenson may have tacitly understood this pattern, based on his great curiosity, constant alert observations, and substantial experience.

He gave an explanation that by making the exit hole small, the burnt air exited the lamp with such high velocity that the flame could not enter (Smiles 1879, p. 93). This is not now viewed as a sound explanation, but he did tacitly know, based on his experience and experiments, the pattern that the small holes would make for a much safer lamp (Smiles 1879, pp. 101-102). And the lamp *did* work.

He tested the lamp himself by walking toward an area of a mine known to have a high level of gas. Observers at the mine who were “more timid and doubtful” followed far behind him (Smiles 1879, p. 95). If his lamp had not worked Stephenson probably would have died in the explosion.

How would we act toward inventors and entrepreneurs if we agreed that they are “little wiser than their primate cousins” (Koppl et al. 2023, p. 59)? I can imagine following George Stephenson, holding the lamp he built, into a gas-filled mine. But I can't imagine following the smartest chimpanzee, holding a lamp that they built, into that same gas-filled mine. Peter Thiel says that “brilliant thinking is rare, but courage is in even shorter supply than genius” (Thiel 2014, p. 5). George Stephenson had courage.

Wilbur Wright left many documents (including many letters) recording what he thought and did. David McCullough has pulled these together in a thoughtful and sometimes lyrical account (McCullough 2015). He finds, for instance, that Wilbur Wright did not simply stroll to his invention. He, with help from his brother, worked and thought very hard for a number of years. Receiving no subsidies from the government, the brothers self-funded their efforts from what they had earned in their Dayton bicycle shop. The generous government subsidies went to Samuel Langley, whose “aerodrome” crashed into the Potomac River after only a few seconds in the air (McCullough 2015, pp. 93, 96-97, and 99-100). Getting airborne could be a challenge, but landing in a controlled way could be an even greater challenge.

Part of what Wilbur Wright did each summer at Kitty Hawk was to implement the experiments he had planned the previous winter at Dayton. Conditions at Kitty Hawk were very harsh—swarms of mosquitoes, heat, winds blowing their tents McCullough 2015, pp. 53, 58-59). But Orville said this was the happiest time of their lives (McCullough 2015, p. 51). Another part of what Wilbur Wright did at Kitty Hawk (and elsewhere) was to study the flight of many birds and develop ideas of how they were able to fly (McCullough 2015, pp. 29, 36-39, 51-53, 67-68, 91-92, 124-125, and 208). Eyewitness John T. Daniels assisted the Wright brothers’s first flight on December 13, 1903. He said, “It wasn’t luck that made them fly; it was hard work and common sense; they put their whole heart and soul and all their energy into an idea and they had the faith” (Daniels as quoted in McCullough 2015, p. 108).

The authors of “Explaining Technology” are willing to grant the Wright brothers enough “foresight and intelligence” (Koppl et al. 2023, p. 16) for the brothers to rule out “locomotives, ink pots, and mustard seeds” (p. 16) as “plausible” (p. 16) components for an airplane. And they are willing to grant that the Wright brothers’s invention involved an “element of planful search” (p. 54). But even with the Wright brothers, Koppl et al. (2023) are keen to deflate the role of human agency. They emphasize that “pure reason” (p. 54) was not enough to know how to “cobble” (p. 55) together the plausible components of an airplane, since even today no “scientific consensus” (p. 54) exists on how lift occurs. They emphasize that, like other technological change, flight "is not so much the product of reason, intelligence, and foresight as of tinkering and improvisation" (p. 55).

Koppl et al. (2023) write that: "although the automobile factory may run on the highest Weberian principle of capitalistic rationality, automobiles are not the product of foresight and rational planning. They emerge from the division of labor like stones heaved out of the New England soil by an autumnal frost" (p. 13). Ponder that statement for a while. The stones are heaved without a single stroke of human agency. Yet if you read accounts of the birth of automobiles you find a lot of human agency and even some foresight and rational planning. William Pelfrey's book asks why we remember Henry Ford and not Billy Durant as the entrepreneur most responsible for that birth (Pelfrey 2006). His answer is that Henry Ford had the foresight to be financially frugal, whereas Billy Durant did not, so following the stock market crash of 1929, Henry Ford was still standing, but Billy Durant was not.

Successful co-founder of PayPal and Palantir, and venture capitalist Peter Thiel's book *Zero to One* is based on a course he taught at the Stanford Business School (Thiel and Masters[29] 2014). I used the book in my Economics of Entrepreneurship seminar partly because Thiel's contrarian views on so many topics stimulate thought and discussion. One of those views is that entrepreneurs need to plan. He says:

> iteration without a bold plan won't take you from 0 to 1. A company is the strangest place of all for an indefinite optimist: why should you expect your own business to succeed without a plan to make it happen? Darwinism may be a fine theory in other contexts, but in startups, intelligent design works best. (Thiel and Masters 2014, pp. 78-79)

The greatest automobile entrepreneur of our time is Elon Musk, who early-on first competed and collaborated with Peter Thiel in the founding of PayPal. The story of Musk's entrepreneurship with Tesla automobiles does not support the claim that they arrived on earth with no more human action than that behind "stones heaved out of the New England soil by an autumnal frost" (Koppl et al. 2023, p. 13).

Shai Agassi's Better Place electric vehicle (EV) startup was celebrated as an exemplar of Israel's bright entrepreneurial future (Senor and Singer 2011, pp. 1-11 and 129). But a key ingredient for the success of EVs is having sufficient efficient charging stations. When Better Place failed, the easy explanation was that Agassi had attempted to make EVs before all of the components existed—meaning before EVs had entered the adjacent possible. But Elon Musk wanted to make EVs happen, so when key components were not good enough he made those components better, not only the charging stations, but batteries also. At first EVs were not adjacently possible, but they were *un*adjacently possible and could be made adjacently possible if one thinks through and executes enough leaps.

Before Tesla, setting up a new automobile company was viewed as an impossible dream. The theory was that the incumbent automobile companies were too big and powerful. To compete an automobile start-up would need to achieve a high sustainable scale of production and sales, before it ran out of money. A lot of components would need to come together. You would need a very good automobile, efficient manufacturing, good-enough distribution and marketing systems, and a lot of funding. Others had tried, Tucker, DeLorean, Agassi, and failed, supporting the theory that a new automobile company was doomed. But Elon Musk surprised the world by doing the impossible. Tim Higgins gives the details in *Power Play: Tesla, Elon Musk, and the Bet of the Century* (2021). Musk did a lot of planning and exercised a lot of foresight. Sometimes his foresight was wrong, and sometimes he modified his plans. But he was very far from just waiting around for the New England soil to heave up a Tesla Model 3.

Elon Musk is an innovative entrepreneur who wants to go to Mars. But several key components that he needs do not yet exist. Since they do not yet exist to be combined, they are not yet part of the adjacent possible. Elon Musk did not give up. He has set about to create the key components.

A common story about entrepreneurship in Africa is that African infrastructure is so lacking, that innovative entrepreneurship there is doomed. But the Tolaram brother entrepreneurs, Sajen and Haresh Aswani, behind the making and selling of Indomie noodles in Nigeria, would not take “doomed” for an answer (Christensen et al. 2019, pp. 79-89). African-made noodles required as components a deep-water port, clean water, and electricity. These components either did not exist or existed with either unreliable quality or too volatile availability. The components were definitely not “just lying around” (Koppl et al. 2023, p. 49) waiting to for someone to “cobble” (Koppl et al. 2023, p. 54) them together. Tolaram had to engage in what has been called “backward integration” in order to create reliable high-quality components (Leke et al. 2018, p, 120). Since some of the components did not exist that they needed to combine to make African-made noodles, that meant that African-made noodles were not part of the adjacent possible.

If there was not the deep-water port they needed, Tolaram built a deep-water port (pp. 80, 84, and 86). If there was not the clean water they needed, Tolaram built a water and sewage treatment plant (p. 86). If there was not the electricity they needed, Tolaram built an electric generating plant (p. 86). "If Tolaram had waited for the Nigerian government to address the "infrastructure" and "institutions" challenges before investing, the company would still be waiting and would likely not be operating in Nigeria today" (Christensen et al. 2019, p. 84). They did not wait for adjacent doors to open and then stroll in; they grabbed a sledgehammer, smashed through the wall, and dashed in.

Ignaz Semmelweis was the doctor who suggested that his colleagues in Budapest wash their hands after performing autopsies and before going on to delivering babies and spreading fatal cases of childbed fever. He had no new theory of what was happening but had been alert to an important pattern and had a sense of urgency about what was at stake. Most of his colleagues ridiculed and dismissed him. He died from the physical trauma he received in a Viennese insane asylum in 1865 (Schneider 2020, pp. 103-106).

Akiro Endo worked at a Japanese pharmaceutical firm trying to derive therapeutic chemicals from fungus. He succeeded in deriving the first statin (Forrester 2015, pp. 274-282). When the initial tests of the statin had ambiguous results, his bosses ordered him to stop the research. He continued the research and showed that the statin was indeed safe and effective, but he was fired for disobeying orders.

Just as Endo found a way to make use of a fungus; Suren Sehgal found a way to make use of an *anti*-fungus. This chemical was found in the dirt on the least adjacent inhabited land in the world, Easter Island, more than 1,200 miles from the nearest fellow humans. A scientific expedition to the island collected dirt near an extinct volcano that eventually made its way to researcher Suren Sehgal at the Canadian pharmaceutical firm Ayerst. Sehgal found a lot of the anti-fungal agent in the dirt, apparently a product of the dirt bacterium *Streptomyces hygroscopicus*. He started experimenting with the anti-fungal agent, that he named "rapamycin" (Attia 2023, p. 75).

But Ayerst decided to close the location where Sehgal worked and instructed him to destroy all the samples he was working on, including rapamycin. He disobeyed the instructions and snuck some home, keeping it in a refrigerator until he found a chance years later to continue his research. Eventually rapamycin was found to suppress the immune system from attacking transplanted organs and now Dr. Peter Attia and other longevity researchers believe that it holds promise for extending our healthspans and our lifespans (Attia 2023, pp. 76-79; see also Diamond 2025). Sehgal at least was not fired.

Frank Hursey at 40 was a curious not-highly credentialed engineer, whose tiny third start-up made and sold huge machines that cranked out oxygen and nitrogen, sometimes making use of the common mineral zeolite, that allowed oxygen to pass through easier than nitrogen (Barber 2023, pp. 20-23). Hursey's curiosity about zeolite led him to the library where he found electron microscope photos that looked like a honeycomb of caverns. "Working entirely on his own" (p. 24), he had a hunch—could the caverns absorb the small molecules of water in blood, leaving a higher concentration in the blood of the larger platelets and proteins that speed clotting?

He bought a mouse at a pet store and cut the mouse. The mouse bled but stopped bleeding when he poured some zeolite on the wound (pp. 25-26). Using zeolite to stop bleeding did not involve combining a lot of components. It involved seeing a new use for a cheap substance that literally had been lying around, part of the adjacent possible, for as long as *Homo sapiens* had been a species. In 2004, Hursey, again working on his own, found that the common mineral kaolin worked as well as zeolite, but without zeolite's side-effect of heating the skin on the edges of the wound (pp. 214-215).

One might assume that with Hursey's zeolite epiphany and his test of it on the mouse, and later on himself, that the "zeolite-to-stop-bleeding" technology would be in the world, available to soldiers and the public. But this was a separate challenge, one that Hursey struggled to master (Barber 2023, p. 28). Ralph Waldo Emerson is widely quoted as claiming 'Build a better mousetrap, and the world will beat a path to your door.'[30] After his epiphany, Frank Hursey got himself ready for the world to beat a path to his door. He sent out 10 letters to companies like Pfizer, Eli Lilly, Schick, and Gillette (p. 27). The only one that responded at all was Johnson & Johnson that sent "a withering sneer of a rejection letter" (p. 27). So Hursey got discouraged, stopped pursuing his invention, and returned his focus to the huge machines that produced oxygen and nitrogen. But once in a while he would lose focus, remember zeolite, and get excited telling someone about it.

For instance when he sought help selling his huge oxygen-nitrogen machines, Frank Hursey conducted a job interview of a struggling salesman named Bart Gullong, and eventually got side-tracked, excitedly telling Gullong what you could do with zeolite. Bart Gullong was concerned:

> That sounded like science fiction to Bart. How could an obscure mineral used in machines also stop people from bleeding? Who would even think to put such a thing in their body? And why would a guy whose business was making oxygen generators spend so much time talking about blood clotting? It made Frank seem like an easily distracted crackpot, which Bart surely hoped he wasn't. (Barber 2023, p. 50)

Gullong was desperate, so despite his concern he took the job anyway, working on commission to sell Hursey's oxygen-nitrogen machines. And although at first it sounded like science fiction, after gradually pondering zeolite further Gullong saw potential for a product that he eventually named QuikClot.

The biggest potential customer for a bleed-stopping product was the Pentagon, but powerful men in the Pentagon had cronies in big pharma who were developing competing products. John Holcomb, the top medical officer for the army advocated a couple of inferior products and refused to give QuikClot a hearing. Gullong was up against the "fatal collision of the arrogance, massive budgets, and unchecked power structure of army medicine" (Barber 2023, p. 225). A few mavericks both inside and outside the Pentagon, rose to the defense of QuikClot. (Some of these mavericks had acquired a sense of urgency by seeing soldiers bleed out in combat.) A key advance occurred when one of the mavericks broke custom and allowed Hursey's small start-up to test its product against the competitors from big pharma. They cut the femoral arteries of large pigs and applied either QuikClot or one of the competing products to each. Only the pigs lucky enough to get QuikClot survived.

Other obstacles arose. Hursey discovered that during the period when he was paralyzed by discouragement, he had absent-mindedly allowed his patent to expire by failing to pay the renewal fees. And Gullong's patent attorney found that a competing patent had been filed. So Gullong went to the holder of the competing patent and convinced him to sign an agreement not to sue (pp. 83-85). The marines and navy ordered QuikClot, (p. 85) but the main potential customer was the army, and Holcomb blocked the army from ordering QuikClot. So Gullong decided to use guerrilla-marketing to show army soldiers and lower-level officers that QuikClot would save their lives (pp. 147-148). Gullong got a lot of testimonials from navy and marine soldiers whose lives had been saved by QuikClot, and then made sure the testimonials were seen and used by many media outlets (pp. 149-150).

Soon Gullong learned that division-level army officers had some funds they could spend on their own for mission-critical needs, and they were going around the top brass to buy QuikClot for their soldiers (pp. 152-153). Holcomb kept pushing a product called Factor 7 that had side effects that were killing soldiers. With some media exposés and pressure from Congress, eventually the whole army came around to QuikClot and Holcomb resigned, only to be hired as Dean of the University of Texas Medical School (pp. 219 and 221). Entrepreneur Bart Gullong had succeeded in bringing QuikClot into the world, available to soldiers and the public.

Those whose lives are saved by QuikClot should thank Frank Hursey, the tinkerer—the intelligent, thoughtful, curious tinkerer. But they should also thank Bart Gullong, the innovative Schumpeterian entrepreneur. An explanation of technology that does not mention the role of Bart Gullong is like an explanation of Shakespeare's *Hamlet* that does not mention the Danish prince, to paraphrase Joseph Schumpeter.

William Coley in the 1890s pioneered immunotherapy for cancer at the Memorial Hospital that would eventually become the Memorial Sloan Kettering Cancer Center (Kinch 2019, pp. 127-131). In 1890 17-year-old Bessie Dashiell (a friend of John D. Rockefeller, Jr.) came to ask the young surgeon William Coley about a persistent pain in her hand. Nothing he knew to do helped her, including eventually amputation of her arm, and months later she died in 1891 at age 18. Dr. Coley was devastated and resolved that if he ever had another case like Bessie's, he would find a way to do better.

He searched the archives to see what he could learn from any cases similar to Bessie's. His eureka moment came with his "serendipitous" discovery of Fred Stein's spontaneously cured cancer (Hall 1997, p. 44). Coley observed that the "spontaneous" cure occurred after Stein suffered from a severe skin infection. Stein had nearly died of the skin infection but when he recovered from it, his cancer was gone too. Coley continued to search the library archives, examine the literature, and question colleagues, inductively seeking and finding a pattern of similar cases where some hopeless patients with advanced metastatic cancer, had been cured after they suffered, and fought off, a severe viral or bacterial infection. As a positive side-effect, the stimulated immune system also killed the cancer.

Based on this pattern, Coley had the insight (hunch) that sometimes, final stage cancers could be cured by the immune response to severe infections. In 1891 he began trial-and-error experiments with toxins. All of his experiments were performed on patients who had exhausted all other options and were expected to die soon from their cancer. Two of these patients died from Coley's early experiments with live bacteria.

Many were cured. Eventually Coley settled on a cocktail of two types of killed bacteria, *Streptococcus pyogenes* and *Serratia marcescens*, for what he called Coley's Toxins.

Dr. James Ewing, the head of research at Memorial, saw radiation as the magic bullet against cancer. When he took charge at Memorial, he marginalized Coley and banned the use of Coley's Toxins in the hospital. Coley received some funding from Bessie's friend, John D. Rockefeller, Jr., but his toxins were strongly criticized in 1894 by the *Journal of the American Medical Association* (*JAMA*) (Munir et al. 2024, p. 2). Partly due to financial challenges following the 1929 stock market crash, and partly due to his marginalization at Memorial, Coley spent increasingly more of his time performing hernia operations at the Hospital for the Ruptured and Crippled, where he also had privileges, eventually also taking on the role of an administrator.

After Coley's death in 1936, his uncredentialled daughter Helen Coley Nauts took the initiative to preserve and organize the records of over 1,000 cancer patients who had been treated with Coley's Toxins. Nelson Rockefeller, a son of John D. Rockefeller, Jr., eventually provided limited funds to help Nauts set up a small foundation to aid her work.

The Mayo Clinic had some success with Coley's Toxins and kept using them through the 1930s and the Lister Institute in London kept making "the toxins at least through 1943" (Hall 1997, p. 74). In 1963, the Food and Drug Administration (FDA) refused to grant Coley's Toxins the "proven drug" status that was granted to legacy drugs like aspirin, implying that if Coley's Toxins were ever to be sold again, they would need to go through the FDA's full battery of Phase 1, Phase 2, and Phase 3 clinical trials (Munir et al. 2024, p. 2). Despite Helen Coley Nauts's unrelenting efforts, immunotherapy researcher Michael Kinch says that immunotherapy was set back half a century by the marginalization of Coley's work (Kinch 2019, p. 130).

Why was Coley's immunotherapy rejected by the credentialed experts of his day? He was a clinician who was not very effective at structuring and presenting his results. Radiation appeared more scientific, with the Nobel Prize behind it. Giving patients an infection to cure cancer seemed like a violation of the Hippocratic Oath. But even with those reasons in mind, it is still hard to justify the reception of Coley's Toxins, because of the evidence that Coley was saving lives that otherwise could not be saved. Not everyone ignored the efficacy of Coley's Toxins. The Mayo Clinic may deserve its high repute.

What do you make of a case where an entrepreneurial physician through great effort and courage puts together the components of a cure, brings it into the world, and it often works, and then it gets buried for 50 years by the dominant credentialled experts?

I can find no evidence that Coley patented Coley's Toxins. (Naturally occurring bacteria cannot be patented, but maybe he could have patented the process for killing and administering them?) The records of his large number of successful hernia surgeries suggest that he was an excellent surgeon. So, it is not obvious that Coley had anything personally to gain from advocating an immunotherapy alternative to the surgical approach that he had thoroughly mastered and for which he was well-paid.

Today William Coley is widely recognized as the Father of Immunotherapy (Munir et al. 2024, p. 3). He looked where others refused to look, and he saw what others refused to see. He did what most others refused to do, and he saved the lives of many whose prognosis was otherwise hopeless. William Coley did not make an incremental advance through an adjacent open door. It took courage and perseverance and urgency. Heroes exist and William Coley was one of them.

Often today, especially against cancer, most of the advances that are announced only bring a few months of added life—months accompanied by severe side-effects. These advances seem to be incremental, but that is not evidence of the ***inevitability*** of incremental-only advance (Raza 2019). The mandate of Phase 3 randomized clinical trials (RTCs) makes drug development extraordinarily expensive. So pharma firms usually focus on developing new drugs that are very similar to already-available drugs, and design them to be given near the end of life, so the Phase 3 RTCs can test the efficacy in just a few years, lowering costs. Drugs tried in early adulthood might have much greater efficacy. But few pharma firms can afford the decades long clinical trials to prove that efficacy, so few such drugs are developed. The incremental-only progress against cancer might seem to support the emphasis in the TAP of advance through the adjacent possible, but the progress is slow, not because of the nature of innovation, but because of the incentives and constraints we impose on medical entrepreneurs.

The FDA could follow the advice of Nobel-Prize-winners Milton Friedman (1973; Friedman and Friedman 1980, pp. 203-210) and Gary Becker (2004) who argue that regulations should at least return to only mandating safety, no longer also mandating efficacy, and thus no longer requiring the exorbitantly expensive Phase 3 trials (see also: Lawrence 2022; Henderson et al. 2025; Hooper and Steiner 2025). Stuart Kauffman, with co-authors, has more broadly discussed the weaknesses of RCTs (including not only Phase 3 RCTs, but also Phase 1 and 2 RCTs) and argued for the strengths of an alternative approach called "quality improvement collaboratives" (Eppstein et al. 2012). If, at a minimum, Phase 3 RCTs were no longer mandated, then more pharma firms could afford to take bigger risks, testing new drugs that are less similar to old drugs, and testing them earlier in patients' lives. *The ubiquity of incremental-only advances is due to policy, not to inevitability, and policy can be changed*. There could have been, and can still be, large leaps. More of Paul Ehrlich's "magic bullets" may still be found (de Kruif 1940).

Incremental innovation is important and occurs in different forms. William Baumol suggested that after small entrepreneurial startups bring us breakthrough innovative leaps, larger incumbent firms often make incremental improvements (Baumol 2005). Incremental innovation can also occur in the form of the stochastic tinkering described in "Explaining Technology," or in the form of the more purposeful user-generated tinkering described in Potts et al. (2025). But leaps also do occur and are important. Any explanation of technology that ends with the incremental is at best seriously incomplete.

Breakthrough inventors and innovative entrepreneurs sometimes pursue goals that many see as impossible, including the credentialled experts. This would be true, for instance, of Filippo Brunelleschi,[31] George Stephenson (in the Chat Moss embankment project), Wilbur Wright (Diamond 2019a, p. 17), and Guglielmo Marconi (Diamond 2012a, pp. 113-115 and 133; Diamond 2019a, pp. 24 and 26). These inventors and entrepreneurs often pursue goals that are not yet part of the adjacent possible. They often make the goals part of the adjacent possible by filling in the components that at first do not yet exist (see Flyvbjerg and Gardner 2023). They usually do more than “cobble together” (Koppl et al. 2023, p. 54) components that “are just lying around” (p. 49), and what they do is usually not easy.

4. **Urgent Need for Actionable Explanations of Technology**

The main problem with the TAP model is that it excludes, or at least “deflates” human agency. The TAP model assumes that inventors and entrepreneurs cannot choose to act differently, and that citizens cannot choose to change institutions or government policy. The authors communicate this in three ways. The first way is in assuming that the parameters are fixed. A more realistic assumption would be that at least *P* varies, based in part on what inventors and entrepreneurs *choose* to do, and on what institutions and government policies *allow* them to do. The second way is to assert that “institutions” and “agent heterogeneity” are “endogenous” (Koppl et al. 2023, pp. 7 and 36-37), affected perhaps by niches and genetics, but unaffected by conscious human agency, and in any event, not affecting technology. “Empires and legal regimes come and go, but the combinatorial evolution of technology” just keeps rolling along (p. 7). The third way is the assertion that the growth of technology is “inevitable” (Koppl et al. 2023, pp. iii, 23, and 24).

All of us know, or have known, people with cancer. We have a sense of urgency about curing cancer. We have some of the "skin in the game" that Nassim Nicholas Taleb (2018) argues is a key source of motivation. What we want to know is what sort of people, pursuing what sort of actions, under what sort of incentives and constraints, under what sort of institutions and policies, will result in the fastest fullest cures? Even if the TAP model perfectly fit all the data in every way, it would not help us know what we should do.

With its assertion of the inevitability of technological progress, the TAP model even implies that we should stop looking for anything to do. But that is not sound advice. Many cases of technological progress reveal that the progress was not inevitable. Entrepreneurs with courage and grit, persevered, often alone, underfunded, and in the case of Ignaz Semmelweis, literally driven insane. But when they did so, they sometimes succeeded in making the world a better place.

We need an explanation that is true, implies many of the stylized technology facts, and is actionable. By "actionable" I mean that it provides some guidance to inventors, entrepreneurs, and policymakers.

5. Alternative Explanations of Technology

Koppl et al. (2023) list several competing alternative explanations of the Industrial Revolution and then claim that the absence of a consensus on which one is right suggests that all of the alternatives are wrong. But there are other reasons for the lack of consensus. One reason there is a lack of consensus is that this is a difficult and important issue. Another is that how the issue is decided will influence current policies, and different theorists have 'skin in the game' on which policies are adopted.

Yet another reason for the lack of consensus is that many scholars believe there can be only a single cause. The simplicity of Occam's Razor has its appeal and endorsing a single cause is simpler than endorsing several. But in choosing explanations, simplicity should be the criterion only when other things are equal. If the truth is that several causes matter, then the truth trumps simplicity. The Industrial Revolution for instance had multiple causes, each of which had to have been met in order for it to have occurred. (I elaborate this point in my otherwise laudatory review (Diamond 2012b) of Deirdre McCloskey's *Bourgeoise Dignity* (2010).)

To wit: for the Industrial Revolution to occur you needed at the same time to have enough rule of law, property rights, ability to self-fund, limited regulations, belief in the possibility of progress[32], and praise for those who invent and innovate. For technological progress to continue I argue (Diamond 2019a) you basically need more of the same.

Each of these causes were present in the actual Industrial Revolution and I believe that each was a necessary condition for the Industrial Revolution to occur. But I suspect that even if all of these necessary conditions were met, they together would not constitute a *sufficient* condition, guaranteeing that the Industrial Revolution would occur. The reason is that even with them all met, you still would need to have enough individuals choose to go to the trouble of being inventors and entrepreneurs.

There is more to be learned that can help us accelerate technological progress. We need to learn more about how inventors and entrepreneurs are thinking and deciding when they succeed. In the rest of this section, I have some tentative observations on that and near the end of this section I will mention Gary Klein's promising research method for learning more.

On their page on the "genius" explanation of technological advance Koppl et al.

(2023) say that the explanation is “common” and “naïve” (p. 5). They say it is “the most common theory outside of academia” (p. 5) and associate it with the “solitary genius or mad scientist” and then parenthetically illustrate by mentioning “Frankenstein” (p. 5). They proceed with a quote asserting that the stories of “heroic geniuses” (p. 6) are folk tales like the myth of Prometheus. Their page quickly “deflates” a view that deserves more serious attention. “Genius” is “a term invented by the Italian humanist philosophers to describe a natural ability for original invention” (King 2000, p. 159).

I have argued, to the contrary, that some inventors and entrepreneurs are correctly viewed as heroes and identifying them as such can inspire others to pursue heroism (Diamond 2019a, p. 131). And parts of the achievements of some inventors and entrepreneurs have indeed been mostly solitary (Diamond 2019a, pp. 5-6). In a similar vein, in the next few paragraphs I argue, using Elon Musk for illustration, that geniuses exist too, and that when we are lucky enough to benefit from their brilliance, we should celebrate rather than chain them.

Some of the role of heroic geniuses in bringing us new technology can be explained and can be explained in a way that is actionable. Samuel Smiles wrote of the lives of great entrepreneurs, seeking explanations (Smiles 1879, 1905). His most important explanation can be expressed in a single word—perseverance. Character is not the whole explanation, but it is part of it. Wedgwood, Stephenson, Wright, Jobs, Musk. They all persevered, some were geniuses, some were heroes, and some of what they achieved can be explained.

Elon Musk has frequently been called a “genius” (Isaacson 2023, pp. 16, 27, 198, 262, and 470; Vance 2015, pp. 17, 34, and 258). Sometimes that label is simply applied to those who find ways to achieve what others saw as impossible or at least very unlikely. But often “genius” implies some cognitive power beyond what most possess. Elsewhere I have discussed how innovative entrepreneurs are often dyslexic and may in some other ways be cognitively diverse (Diamond 2019, p. 24).

Susan Cain’s book *Quiet* for instance makes a powerful case for the creativity and productivity of introverts, of the solitary (Cain 2012). Besides introversion, another related trait common to geniuses is intensity (Schilling 2018a).[33] Inventors or entrepreneurs who are bipolar have periods of great intensity. Gail Saltz argues that being moderately bipolar may enable greater creativity in a variety of fields (Saltz 2017, pp. 131-152). When Jon McNeill was President of Tesla, he asked Elon Musk if Musk was bipolar and Musk replied that he probably was (Isaacson 2023, pp. 268-269).

Elon Musk is clearly self-aware that he is cognitively diverse. Early-on he asked his first biographer: “Do you think I’m insane?” (Vance 2015, pp. 1, 4, and 345). When Musk hosted Saturday Night Live (SNL) he identified himself as on the Asperger’s spectrum (Isaacson 2023, p. 377). Musk’s mother Maye agrees with him that he is on the spectrum though saying he never was tested for it as a child (Isaacson 2023, p. 19). Many identify Musk’s extraordinary ability to focus as an aspect of his cognition. Walter Isaacson emphasizes Musk’s

> tendency to zone out and retreat into his own world when thinking. “Ever since I was a kid, if I start to think about something hard, then all of my sensory systems turn off,” he says. “I can’t see or hear or anything. I’m using my

brain to compute, not for incoming information." (Isaacson 2023, p. 17) Musk's ability to focus, absenting himself from ordinary conversation and distractions, is plausibly of great use in pursuit of his inventive and entrepreneurial goals. Perhaps it is the stuff of genius.

In the end some aspects of genius may remain unexplained, perhaps because of our failure to study genius hard enough or in the right way, or perhaps because it is indeed inexplicable. Srinivasa Ramanujan came out of India to Cambridge with little formal training or peers and jotted down many brilliant mathematical theorems. He died at age 32 at Cambridge with no one, at least so far, understanding the source or method of his genius (Kanigel 1991).

Gary Klein, in books like his *Seeing What Others Don't* has made some progress in explaining the sources of insights more generally (Klein 2013). Maybe we would understand more about genius if more of us, like Klein, spent time observing and pondering the creative process. But let's say, pessimistically, that some aspect of genius is indeed fundamentally inexplicable. That would not be a reason to deny and dismiss genius—we still should want to identify, protect, and praise it. When a genius enters our lives we should feel fortunate and welcome him. But genius is not a necessary condition of breakthrough invention or innovative entrepreneurship, which can also be enabled by other forms of cognitive diversity or by ordinary people who choose to persevere and work hard.

Victorian era biographer Samuel Smiles provided a rich array of examples to document how ordinary people could achieve great projects through perseverance and hard work (Smiles 1905; see also Smiles 1879 and his other books). Smiles often used the word "projector" when today we would say "entrepreneur" (e.g., Smiles 1879, passim). The roots of the word "project" mean throw forward. A projector is one who seeks to bring into being something that does not yet exist. Some projectors have found their ideas for what to bring into existence in stories of science fiction.

Koppl et al. (2023) claim that "combinations that have not entered the adjacent possible are generally unimaginable" (p. 50). But many fiction writers, especially writers of science fiction, imagine worlds and technologies that are not yet part of the adjacent possible. Sometimes these stories are the inspiration for inventors and entrepreneurs to try to bring the technologies into the world. Nobel-prize-winning economist Simon Kuznets even once speculated that sometimes science fiction could provide better predictions about the future than economics (Kuznets as paraphrased by Robert Fogel 2005, p. 13).

Some inventors and entrepreneurs are inspired by science fiction to pursue imagined technologies that require combinations that have *not* currently "entered the *adjacent* possible" but *have* entered the *un*adjacent possible. A would-be inventor or entrepreneur could be alert to when a key component of their imagined technology comes into existence, or if the goal is urgent enough to them, they could take action to bring the key component into existence. Steve Jobs can illustrate both possibilities.

No portable MP3 player was "insanely great" [34] before 2001. Jobs had in mind for Apple to create one that *was* insanely great, but he had another project that was more urgent to him, so he was willing to wait until a key hardware component came into existence.[35] The more urgent project was to set up the iTunes media library and app, that gave consumers cheap and convenient access to a huge array of content.

While iTunes was an insanely great product in its own right when released in January 2001 (Isaacson 2011, p. 383), it could also be viewed as eventually a non-hardware component of the iPod, that mightily contributed to making the iPod itself insanely great.

The key hardware component that was missing from other firms's pre-2001 MP3 players was the capacity to hold a large number of songs, or more concretely, the missing key hardware component was a small-enough, cheap-enough, high-enough capacity storage device. When Jobs learned, in February 2001 (Isaacson 2011, p. 385) that Toshiba was starting to make a miniature hard drive, he realized that the key component now existed, and so what was to become the Apple iPod had entered the adjacent possible (Diamond 2019a, p. 29). Thus the iPod is the kind of case where the entrepreneur waits until someone else brings the key component into existence, allowing an imagined technology, the insanely great iPod, to enter the adjacent possible. But notice that it was plenty easy for Jobs to roughly imagine the insanely great iPod *before* it had entered the adjacent possible.

The other kind of case is where the imagined technology is more urgent to the entrepreneur, like the iPhone was to Jobs in 2006. Jobs wanted the device to be light-enough, with a big-enough screen, and be durable-enough to delight users. That implied that a key component would be light-enough, cheap-enough, strong-enough glass for the screen. Jobs heard that someone at Corning had invented such a glass. Corning did not see a market for it and so shelved it. Because the glass was not "just lying around," Jobs invited Corning CEO Wendell Weeks to visit Apple, where Weeks explained the chemistry behind what came to be called "gorilla glass." Jobs was impressed and said Apple would buy as much as Corning could produce in the next six months. Weeks demurred, saying Corning was not manufacturing gorilla glass and did not have the factory capacity to start.

Jobs was unwilling to accept that answer (Isaacson 2011, p. 471). People who had worked with Steve Jobs, dating back to Apple co-founder Steve Wozniak, say that Jobs could emit a "reality distortion field" that could convince a person that something was possible that they previously were sure was impossible (Isaacson 2011, pp. 117-118 and passim; see also: Schlender and Tetzeli 2015, p. 11; Price 2008, p. 116). So Jobs turned on his reality distortion field with the Corning CEO:

> "Don't be afraid," Jobs replied. This stunned Weeks, who was good-humored and confident but not used to Jobs's reality distortion field. He tried to explain that a false sense of confidence would not overcome engineering challenges, but that was a premise that Jobs had repeatedly shown he didn't accept. He stared at Weeks unblinking. "Yes, you can do it," he said. "Get your mind around it. You can do it." As Weeks retold this story, he shook his head in astonishment. "We did it in under six months," he said. "We produced a glass that had never been made." (Isaacson 2011, pp. 471-472)

When Weeks left Jobs's office, Corning had committed to manufacture the iPhone's gorilla glass.

Elon Musk is another entrepreneur who has decided not to wait for others to bring into existence the key components of his project—in his case a mission to Mars (Berger 2021, 2024). Reid Hoffman, founder of LinkedIn, worked with Musk when Musk was active co-founding PayPal. He says "Elon starts with a mission and later finds a way to backfill in order to make it work financially. . . . That's what makes him a force of nature" (Isaacson 2023, pp. 92-93). Musk also backfills the key *components* of the mission.

What was the source of Musk's mission in life? Surely it was not the desire to "cobble together" components that "are just lying around." One source identified by Musk's most recent biographer, Walter Isaacson, is his early and extensive reading of science fiction (Isaacson 2023, pp. 30-31).[36] This source was already apparent to Musk's first biographer, Ashlee Vance: "For Musk, the call to ensure that mankind is a multiplanetary species partly stems from a life richly influenced by science fiction and technology" (Vance 2015, p. 344). Musk himself tweeted "Foundation Series & Zeroth Law are fundamental to creation of SpaceX" (Isaacson 2023, p. 31). The Foundation Series is a set of science fiction books by Isaac Asimov and the Zeroth Law is from Asimov's *Robots and Empire* (1985).

Musk gave a speech in front of his SpaceX Starship: ""There have to be things that inspire you, that move your heart," Musk said in his speech. "Being a space-faring civilization, making science fiction not fiction, is one of those"" (Isaacson 2023, p. 476). Musk's inspiration from science fiction is not limited to the Starship, but also includes the Optimus humanoid robot Musk is developing at Tesla and the chip-in-the-brain technology he is developing at his Neuralink venture:

> Like Optimus, the idea for Neuralink was inspired by science fiction, most notably the *Culture* space-travel novels by Iain Banks, which feature a human-machine interface technology called "neural lace" that is implanted into people and can connect all of their thoughts to a computer. "When I first read Banks,"

> he says, "it struck me that this idea had a chance of protecting us on the artificial intelligence front." (Isaacson 2023, p. 400)

Isaacson recounts Musk discussing whether Optimus should drive a Robotaxi: ""Do you remember the original Blade Runner movie did something like that," Musk said. "Also the most recent Cyberpunk game." He liked taking the fiction out of science fiction" (Isaacson 2023, p. 485).

One key component of sustainable travel to Mars is the technology to recover the early stage of rockets (Isaacson 2023, p. 226). Through thinking and systematic trial and error, but not casual tinkering with what is "just lying around," Musk has managed to bring that key component into existence. When the first stage of the Falcon 9 reentered to land upright on the landing pad for the first time, Musk became "delirious with joy" and the control "room erupted in applause and cheers" (Berger 2024, p. 206). Here again, the technology to get to Mars had been imaginable, but not yet part of the adjacent possible, since not all of the key components were yet in existence to be combined together to make travel to Mars happen.

Elon Musk is far from the only inventor or entrepreneur to be inspired by science fiction. Much less well-known, but of even greater significance, is the example of Leo Szilard. At the start of the twentieth century, the National Academy of Engineering selected the 20 "greatest engineering achievements of the twentieth century" (Wulf 2000, p. 5). "The main criterion for selection was not technical "gee whiz," but how much an achievement improved people's quality of life" (Wulf 2000, p. 5). Number 19 on their list was: "Nuclear Technologies—From splitting the atom came a new source of electric power" (Wulf 2000, p. 7). The key technology was to split the atom so that more energy came out of the split than went in to cause the split. Leo Szilard was inspired to figure out how to split the atom in a way that starts a nuclear chain reaction by reading H.G. Wells's science fiction book *The World Set Free* (1914).

James Watson, the co-discoverer of the structure of DNA, said that no one had influenced him more than Leo Szilard and that "Leo got excited about something before it was true" (Lanouette 2013, p. XVII). Szilard's biographer William Lanouette gives an example: "H. G. Wells excited him with both science fiction and political inventiveness" (Lanouette 2013, p. 36). By 1932, Szilard's interest in physics had waned, but he found it reignited by big ideas raised by H.G. Wells: "After reading and talking to H. G. Wells, Szilard believed that human survival depended on colonizing other solar systems, and the atom seemed the only power source capable of sustaining space travel" (Lanouette 2013, p. 105; see also p. 141). So Szilard concentrated his thought on how nuclear power could be made possible. Szilard said he had an epiphany during a walk, waiting for a streetlight to turn green:

> As I was waiting for the light to change and as the light changed to green and I crossed the street, it suddenly occurred to me that if we could find an element which is split by neutrons and which would emit *two* neutrons when it absorbed *one* neutron, such an element, if assembled in sufficiently large mass, could sustain a nuclear chain reaction. I didn't see at the moment just how one would go about finding such an element or what experiments would be needed, but the idea never left me. (Szilard as quoted by Lanouette 2013, pp. 137-138; italics in original)

His epiphany revealed to him two of the components needed for nuclear power.

One was an element that would release two neutrons when split by one neutron.

The other was to achieve a critical mass for a chain reaction to occur. These components might not exist, or if they existed might not be easily found. If they did not exist, maybe they could be created, maybe not. Surely they were not adjacent and were not "just lying around." Szilard looked for the needed element. On March 12, 1934, he filed a patent suggesting that it was probably beryllium, but might be uranium or thorium (Lanouette 2012, p. 144).

Szilard worked with Enrico Fermi "for more than two years . . . to design and build the first reactor" (Lanouette 2012, p. 252). On the night before the reactor was to be tested, Szilard thought it would work but was worried that if it ""works too well" there might be an explosion" (Lanouette 2012, p. 250). So he decided to treat himself to a second dinner with a psychologist friend, saying: "even the greatest theoretical physicists cannot be absolutely certain. So I felt that a second dinner was in order" (Szilard as quoted in Lanouette 2012, p. 250). The following morning, on December 2, 1942, the test worked well—critical mass was achieved, resulting in the world's first controlled nuclear chain reaction.

Though seldom rising to the level of importance of Leo Szilard and Elon Musk, many other examples have been suggested where science fiction may have inspired science fact. Pagan Kennedy interviewed Martin Cooper who invented the cell phone. She says:

> Cooper told me that he taught himself to explore imaginary worlds and futuristic possibilities. As a child, "I read a lot of fantasy and mythology, and when I got older I started to read science fiction. So my mind has been floating around forever, which is not a very good attribute for somebody who wants to be an

> executive," he said. But that powerful mind's eye was Cooper's head lamp, one that allowed him to see into the future. "When you combine the attribute of dreaming with an interest in science and how things work (and that's always been important to me), you're just naturally constantly thinking of how things could be done differently," he said. (Kennedy 2016, p. 105)

Martin Cooper was inspired to invent the first portable cell phone by the wristwatch communicator of comic strip detective Dick Tracy (Kennedy 2016, p. 104; Hrdy and Brean forthcoming 2026).[37]

In her favorable description of the ideas of Russian science fiction writer and inventor Genrich Altshuller, Kennedy quotes him as saying:

> Very often, the ideas of fiction writers are directly used during the early development stage of a new field of science and technology . . . [Science fiction] "helps overcome psychological barriers on the road to 'crazy' ideas. (Altshuller as quoted by Kennedy 2016, p. 142)

Camilla Hrdy [sic] and Daniel Brean speculate in slightly more detail on how science fiction can help:

> When science fiction posits plausible, albeit currently impossible, inventions, this can stimulate "nonobvious" thinking among scientists and expand the semantic universe for the discourse about science and technology. Thanks to science fiction, we have forums, phraseologies, and archetypes that help us think and talk about inventions that humans can imagine, but not yet practice. Thus, not unlike patents, "enabled" science fiction can positively impact innovation itself, serving as the inspiration for many of the inventions that we

> see today, from the submarine to the electric car to the iPhone. (Hrdy [sic] and Brean 2021, p. 401)

Science fiction, as distinguished from fantasy fiction, must satisfy the requirement "that it should be *possible*—involving things that we might actually create, . . ." (Hrdy and Brean 2021, p. 404; italics in original).

Both Intel and Microsoft have collaborated with science fiction writers to help them brainstorm on how future technologies "might influence the world and people's lives" (Zoccarato et al. 2024, p. 1; see also Michaud and Appio 2021, p. 129). Intel collaborator and science fiction writer Brian David Johnson says, "I use science fiction based on science fact to help build better technology solutions" (Zoccarato et al. 2024, p. 1).

Here is a list of a few other inventions or innovations that arguably have been partly inspired by science fiction.[38]

- Simon Lake was inspired to invent better submarines by reading *Twenty Thousand Leagues Under the Sea* (1873) by Jules Verne (Hrdy and Brean forthcoming 2026). Hrdy and Brean quote from Lake's autobiography:

  > Jules Verne was in a sense the director-general of my life. When I was not more than ten or eleven years old I read his *Twenty Thousand Leagues under the Sea* and my young imagination was fired. This generation may have forgotten that Verne was a great scientist as well as the writer of the most romantic fiction of his day. I began to dream of making voyages under the waters, and of the vast stores of treasure and the superb adventures that awaited subaqueous pioneers. But with the

> impudence which is a part of the equipment of the totally inexperienced I found fault with some features of Jules Verne's Nautilus and set about improving on them. (Hrdy and Brean forthcoming 2026)

- Robert H. Goddard invented liquid-fueled rockets making use of the work of Hermann Oberth, whose escape velocity calculations compared favorably “with his hero, Jules Verne” (Hrdy and Brean 2021, p. 415).
- Jeri Ellsworth was inspired to develop her start-up CastAR’s augmented reality glasses by Chewbacca playing holographic chess on the Millennium Falcon. The game “was pretty far-out in the 1970s when Jeri Ellsworth saw it in the original *Star Wars*. It took decades for technology to catch up” (Wingfield 2016).
- Franky Zapata was inspired by science fiction films *Back to the Future* and *Iron Man* to invent his jet-powered hoverboard that he used to cross the English Channel in 2019 (Michaud and Appio 2021, pp. 123-124).

Science fiction is not the only source of imagination about future technology.

Authors have also used formats besides science fiction to predict the technological future or to warn of possible future technological dangers or to advocate for future technological benefits. Vannevar Bush’s futuristic "As We May Think" (1945) is a famous example, in which he advocates for his imagined Memex machine that had some of the features of modern computers and the World Wide Web (Kennedy 2016, pp. 108-111 and 153; see also Nyce and Kahn 2003). The Memex inspired Doug Engelbart, computer visionary and inventor of the mouse, to try to invent a machine that could do some of what Memex was imagined to do (Kennedy 2016, pp. 111-112).

He partially succeeded by the mid-1960s (Kennedy 2016, p. 114).

The point of documenting examples of inspiration from science fiction and futurology is not to deny that sometimes inventors and entrepreneurs look at what components are available and experiment with what can be made from them. Tinkering does happen. The point is that not all technology can be explained by explaining tinkering. Sometimes inventors and entrepreneurs imagine a distant goal that requires components that do not yet exist, or at least that are not "just lying around," not adjacent. When these distant technologies are achieved, they are often the greatest achievements of human agency (flight, moon landing, nuclear chain reaction). Technologies inspired by science fiction and futurology are worth studying because at their start they are most clearly not adjacent.

The difference between incremental advances and leaps forward can be expressed in a football analogy. One way to make progress in football is to grind it out slowly through the ground game—a few yards gained each play, at small risk. The other way to make progress is by the forward pass, that has greater gains, at greater risk. Among passes, some are short and some are long. The long pass ("throw deep") has the potential for greatest gain, but also the greatest risk of failure to connect, or at worst, the greatest risk of an interception. When scientists met with Ronald Reagan to seek funding for a new nuclear Superconducting Supercollider that would search for the Higgs boson fundamental particle, Reagan approved the basic science project, signaling his approval with the advice to the scientists to "throw deep" (Sample 2013, p. 129).

If we want to make further progress in "explaining technology," we should focus more on what the inventor and entrepreneur are thinking and doing when they advance technology. We could apply to inventors and entrepreneurs the methods that Gary Klein and his fellow Naturalistic Decision Making researchers have applied to understand the thought and actions of firefighters (2017, pp. 65-69 and passim), nurses (2017, pp. 77-78), and other decision makers.[39] We could embed, observe, and question current inventors and entrepreneurs.

When a firefighter faces a novel emergency, he searches for any times he or others faced previous emergencies that were in any way similar. He asks himself whether anything that worked in that previous emergency might work in the new emergency. He does a mental simulation of how the projected course of action would play out. He does not look for the optimal solution—he finds one that he thinks will work, and then he acts.[40] Sometimes if nothing comes to mind he uses his tacit experiential, or explicit scientific, knowledge of the practical physics of how different kinds of objects act in the world, to create a novel course of action, as Wag Dodge did when the fire raced toward him up the steep hill in Mann Gulch (Klein 2013, pp. 80-85; Maclean 1992).

While we await researchers to apply Klein's research program to current inventors and entrepreneurs, we need not be idle. In discussing the sources he used to develop his explanations of technology, Brian Arthur wrote: "those that turned out to be most useful were the detailed and beautiful case studies of the historians on how particular technologies came into being" (Arthur 2009, p. 11).[41] Such case studies, and the narrative explanations based upon them, are examples of what Deirdre McCloskey once advocated as "thick" methodologies, "thick" as in empirically rich, and as opposed to the empirically "thin" methodology of mathematical formalism (McCloskey 1988).

Narrative explanations are defended by Stuart Kauffman in his latest book *A World Beyond Physics*: "Could you write an equation for this? How would you know what to write? This story is pretty much what you need to know. What would mathematics do here at all?" (Kauffman 2019, p. 103). And a little later he adds "We tell it as a narrative. What else can we do?" (p. 112). If a narrative is good enough for the biosphere, it is good enough for the technosphere too.

From what we know so far, based on extensive technology case studies and biographies of inventors and entrepreneurs, breakthrough inventors and innovative entrepreneurs do not simply “cobble together” (Koppl et al. 2023, p. 54) components that “are just lying around” (p. 49), “little wiser than their primate cousins” (p. 59). They sometimes pursue an ambitious imagined technology that they do not yet fully know how to create. And they sometimes are intentionally looking for, or creating, components that might work in the creation of the imagined technology, sometimes based on mental simulations of how similar or analogous components worked in previous experiences.

6. Conclusion

The authors of “Explaining Technology” explicitly aim to “deflate” alternative accounts, including most notably those that emphasize human institutions and the agency of breakthrough inventors and innovative entrepreneurs. This deflation of human agency also is preserved in Steven Johnson’s famous popularization of the adjacent possible. He asks us to think of technology as a magic house. Whenever we enter a room for the first time, doors appear in that room, leading "magically" to newly adjacent rooms. Each room represents a new tool. So all we need to do to get a new tool is to "open one of those doors and *stroll* into that room" (Johnson 2010, p. 31, *my* italics). The breakthrough inventor and the innovative entrepreneur do not live in this magic house of the adjacent possible. They do not open existing doors and stroll through. They grab sledgehammers and break through obstacles or find ways to pivot around them. Toward distant goals they sometimes slog through a mire, or sometimes hack through a jungle, or when they are lucky and the path is firm, clear, and straight, they sometimes sprint. But what they *never* do is *stroll*.

The gracious, erudite, and witty Stuart Kauffman quotes the early Greek philosopher Heraclitus as saying, "The world bubbles forth" (Heraclitus as quoted in: Kauffman 2023, about 00:04; Kauffman 2019, p. xii). This may be true of evolution in the biosphere, but in the technosphere QuikClot did not just bubble forth. The structure of zeolite had to be seen, a new use for that structure had to be imagined and tested, ignorant or corrupt skeptics had to be convinced or overcome, patent applications had to be written and filed, funds had to be raised, and production at scale had to be organized. Innovative entrepreneurs are not just standing around watching the bubbles emerge in a boiling cauldron like the witches in Macbeth. ("Fire burn and cauldron bubble.") What innovative entrepreneurs do is not inevitable and it is not easy.

The TAP theorists write that they "owe much to Brian Arthur's (2009) theory of 'combinatorial evolution'" (Koppl et al. 2023, p. 1; see also p. 12). When the prestigious and controversial McKinsey management consulting firm hired Brian Arthur to give management advice, they were frustrated to find that he had nothing to say

(McDonald 2013, p. 217). If technological progress is inevitable, then it will happen no matter what management strategies you have, so there is no management advice to give.

If we "deflate" the roles of inventors and entrepreneurs, and if in fact their roles *do* matter, won't we run the risk of discouraging them, and of undermining the institutions and policies that enable them to act? And if we discourage and undermine won't we slow the pace of technological innovation, including the discovery of cures for diseases like cancer? Is Deirdre McCloskey entirely wrong in suggesting that if we honor and dignify invention and entrepreneurship, we will tend to get more invention and entrepreneurship?

Technological progress is not always incremental, inevitable, or adjacent. It is often ***not*** a story of strolling through open doors or "tweaking" what is "just laying around." If we channel Joseph Schumpeter, we might say that to describe technological progress without the innovative entrepreneur's urgency, focus, courage, and perseverance "is like *Hamlet* without the Danish prince" (Schumpeter 1950, p. 86). Technology does not create on its own, people do—especially breakthrough inventors and innovative entrepreneurs. At the start of his magisterial *Principles of Economics*, Alfred Marshall quotes Charles Darwin's "*Natura non facit saltum*" meaning "nature does not make a leap"[42] (Darwin 1860, p. 173; Marshall 1961 vol. 1, p. iii). Biologists still debate whether Darwin was right. But innovative *entrepreneurs make leaps*.

Endnotes

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[1] Robert Lucas once famously wrote that when you start thinking about economic growth "it is hard to think about anything else" (Lucas 1988, p. 5).

[2] Israel Kirzner's entrepreneur is mainly alert to opportunities to buy low and sell high: an arbitraging of markets that happily but unintentionally brings them closer to equilibrium (Kirzner 1973).

[3] A few others have also worried about the absence of the innovative Schumpeterian entrepreneur in the "Explaining Technology" TAP model. Sinclair Davidson (2025) criticizes "Explaining Technology" because "it overstates the inevitability of innovation and downplays the role of institutions, human imagination, and entrepreneurial agency" (p. 0). Saul Estrin, Moren Lévesque, Tomasz Mickiewicz, and Mark Sanders (2025) elaborate on the "Explaining Technology" TAP model by adding innovative entrepreneurs to bring to the market some of the technologies generated by the "Explaining Technology" TAP model. Besides restoring rightful credit to the innovative entrepreneurs, Estrin et al. (2025) view their elaboration as a plausible way to avoid the unfortunate implication of "Explaining Technology" that following the Industrial Revolution inflection point, the number of goods quickly accelerates to infinity. Bart Wilson (2025) does not criticize "Explaining Technology" specifically for the absence of the innovative Schumpeterian entrepreneur but does criticize "Explaining Technology" more broadly for the absence of a *Homo sapiens* level mind, capable of the kind of longer-term planning needed to combine simpler tools into more complex tools (Wilson 2025, p. 5).

[4] The first use of the phrase "stylized fact" is commonly attributed to economist Nicholas Kaldor (1961). As of 2016, Daniel Hirschman found 6,299 social science articles that used the phrase in journals indexed in JSTOR through 2008 (Hirschman

2016, pp. 609 and 622, endnote 10). Of these articles roughly 80% were published in economics journals (p. 609).

[5] Koppl et al. (2023) do not use the phrase "inflection point" but they do write of a "sudden takeoff around 1800" (p. 23).

[6] But for the past few decades a substantial literature has critiqued the procedures we use for measuring GDP, mainly for inadequately accounting for the introduction of new goods and services or for changes in the quality or features of old goods and services. A couple of the important papers in this literature are Griliches (1994) and Nordhaus (1997).

[7] This assumption is also stated, but not justified, at the bottom of Koppl et al. 2023, p. 26.

[8] Brian Arthur tells us that a "prospective publisher" of his *The Nature of Technology*, "suggested I stick with something simple, such as the pencil" (Arthur 2009, p. 13).

[9] I do not rule out the commit-to-a-theory-and-then-test-it method but believe that an empirically rich abductive method of Bayesian updating can usually be more fruitful.

[10] Not all models of combinatorial technology evolution imply a singularity where the "model no longer applies." For instance, when Brian Arthur and his colleague Wolfgang Polak created a simulation model of combinatorial technology evolution, they "found periods of quiescence, followed by miniature "Cambrian explosions" of rapid evolution" (Arthur 2009, p. 203).

[11] Geologists voted overwhelmingly that the so-called "Anthropocene" should *not* be counted as a new epoch (Zhong 2024).

[12] Independent of co-authors, Stuart Kauffman suggests that part of a specific solution to the crisis of the Anthropocene may be the widespread use of Johnson-Su compost (Kauffman 2023, at about 10:17).

[13] The second-generation of the iMacs were even "cooler" than the first "because they came with a simple slot drive for CDs, replacing the clunkier drawer that came with the first ones" (Schlender and Tetzeli 2015, p. 239), suggesting that Jobs not only made Apple's offerings less diverse, he also made them less complex.

[14] Perhaps a circuitous interpretation could save the implication if, for the complexity calculation, you recursively count the components of the components (and so on) as part of the total number of components of the final good? Koppl et al. (2023) are themselves unsure on how to define the components that should be used in the measurement of complexity (see: Koppl et al. 2023, pp. 3-4 and especially p. 4, footnote 2). But in their example (p. 33) of how many components went into "the earliest stone tools" ("just one piece") and "a modern automobile" ("about 30,000 pieces") they seem to be using the straightforward interpretation, and not availing themselves of the circuitous interpretation, of complexity.

[15] Arguably this simplification came at the cost of greater complexity of the processor chip itself. But see the above endnote #13.

[16] The ever-witty economics Nobel Prize winner Robert Solow once wrote of Nicholas Kaldor's stylized facts: "there is no doubt that they are stylized, though it is possible to question whether they are facts" (Solow 1969, p. 2).

[17] I am not clear whether the TAP model implies the continued truth of Moore's Law, predicting that the power of processor chips would continue to increase exponentially.

Most experts on Moore's Law agree that it is no longer true (Peper 2017, Shalf 2020). Is the violation of Moore's Law compatible with the TAP model?

[18] In their model when the extinction rate is above the critical value, it leads "to total system extinction" and when below the critical value it is "irrelevant at late times" (p. 3). So they conclude that the extinction rate "is not a very crucial parameter" (p. 3).

[19] Filippo Brunelleschi studied ancient domes in Rome as a starting point for building the Duomo in Florence (King 2000, pp. 5 and 26-28). For hundreds of years the ancient domes had been adjacent, but there had been no incremental progress toward the Duomo. Only with Brunelleschi's inventions, for instance in the pattern of brick laying (pp. 97-99) and in the hoisting of heavy stones (pp. 66-69), did the Duomo leap into existence.

[20] More than one source says that the quote can be found on the web site of Peter Thiel's venture capital Founder's Fund. I was unable to find it there in October 2025.

[21] In 2024 the leading source country for patents filed with the E.P.O. was the U.S. The source for this fact and for the number of patent applications filed with the E.P.O. is the web site of the E.P.O. (https://www.epo.org/en/news-events/press-centre/press-release/2025/1352247). All of the countries in the E.U. also belong to the E.P.O. and in addition the E.P.O. includes "Albania, Iceland, Liechtenstein, Monaco, North Macedonia, Norway, San Marino, Serbia, Switzerland, Turkey, and the United Kingdom" (https://www.uspto.gov/patents/basics/international-protection/international-filing-0#:~:text=Breadcrumb,patent%20granted%20by%20the%20EPO). A web site of the U.S.P.T.O. states the number of patent applications for FY2024 as 793,824 (https://www.uspto.gov/dashboard/patents/production-unexamined-

filing.html#:~:text=Table_title:%20Utility%2C%20Plant%2C%20and%20Reissue%20(UPR)%20Patent,FY2025%20(Sep%2D25)%20%7C%20Application%20filings:%20612%2C266%20%7C).

[22] A web site of the E.U. estimates the E.U. population at about 449.3 million on Jan. 1, 2024 (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_structure_and_ageing#:~:text=update:%20February%202026.-,Highlights,%2D0.1%20years%2C%20respectively). A web site of the U.S. Census Bureau estimates that the population of the U.S. was about 335,893,238 on Jan. 1, 2024 (https://www.census.gov/library/stories/2023/12/happy-new-year-2024.html).

[23] Brian Arthur writes, to the contrary, that Schumpeter uses the word "innovation" "confusingly, to my taste" (Arthur 2009, p. 100).

[24] "Motive power—you can't imagine how important that is. That's the heart of everything" (Rand 1957, p. 63).

[25] Mitchell says: "So, I've learned how much of our intelligence is invisible to us: how all the time we're able to make generalizations and transfer what we've learned to new situations, and make abstractions, and metaphors, and so on in a kind of invisible way. We don't even know we're doing it. And this is, I think, is one of the reasons that people misjudged how hard AI would be. We have all these people like Marvin Minsky back in the 1960s predicting that we'd have human level machines in 15 years from then, and it's still going on; and I think that we still don't recognize how much of our intelligence is below the surface" (Mitchell 2020). If Mitchell is right, and if AI does not have, and cannot acquire, a similar store of unarticulated knowledge, then

AI's chances of surpassing our intelligence, and especially our capacity to innovate, are diminished. See also Mitchell (2019, p. 104).

[26] Another example of Stephenson's "intuition" was his "remarkable" ability to almost always pick out at first glance, what turned out to be the best route for a new rail line. Smiles says: "His companions used to remark his singular quickness of observation. Nothing escaped his attention—the trees, the crops, the birds, or the farmer's stock; . . . . When taking a flying survey of a new line, his keen observation proved very useful to him, for he rapidly noted the general configuration of the country, and inferred its geological structure. He afterwards remarked to a friend, "I have planned many a railway travelling along in a postchaise, and following the natural line of the country." And it was remarkable that his first impressions of the direction to be taken almost invariably proved correct; . . ." (Smiles 1879, p. 261).

[27] Smiles writes that to others the locomotive engine "was still regarded as a curious and costly toy, of comparatively little real use." But Stephenson "had at an early period detected its practical value, and formed an adequate conception of the might which as yet slumbered within it; and he now bent his entire faculties to the development of its extraordinary powers" (Smiles 1879, p. 62). Smiles also praises Stephenson's skill at selecting assistants and workers due to "that intuitive knowledge of character, which Stephenson possessed in so remarkable a degree" (Smiles 1879, p. 269).

[28] Barrister Harrison said of Stephenson's plan to route the Liverpool and Manchester line over Chat Moss: "Every part of this scheme shows that this man has applied himself to a subject of which he has no knowledge, and to which he has no science to

apply" (Smiles 1879, p. 166). Smiles says that those opposed to the Liverpool and Darlington line “stigmatized” Stephenson “as an ignoramus, a fool, and a maniac–that even his friends seem for a time to have lost faith in him and in the locomotive system, whose efficiency he nevertheless continued to uphold” (Smiles 1879, p. 170).

[29] Blake Masters was a student in Thiel’s class at Stanford who paid close attention, took very good notes, and helped Thiel turn the notes into *Zero to One*.

[30] The Quote Investigator web site has a thorough account of the versions and sources of the quote (https://quoteinvestigator.com/2015/03/24/mousetrap/). The site suggests that in his known published works, Emerson never wrote anything very close to the usual quotation, although he did express a similar sentiment: “Common Fame. I trust a good deal to common fame, as we all must. If a man has good corn, or wood, or boards, or pigs, to sell, or can make better chairs or knives, crucibles or church organs, than anybody else, you will find a broad hard-beaten road to his house, though it be in the woods” (Emerson 1912, p. 528).

[31] Brunelleschi’s Duomo in Florence is more properly named the Cathedral of Santa Maria del Fiore. “The unbuilt dome of Santa Maria del Fiore had . . . become the greatest architectural puzzle of the age. Many experts considered its erection an impossible feat” (King 2000, p. 5, my ellipsis). Of the largest dome of the ancient world (Hadrian’s Pantheon in Rome, repurposed later as the church Santa Maria Rotonda): “The modern Romans and pilgrims alike were amazed by the immense dome. With no visible signs of support, it seemed to defy the laws of nature. They called it the “house of devils,” attributing its construction not to the skilled engineers of the ancient world but rather to the sinister forces of demons” (King 2000, p. 27).

[32] Anton Howes is working on a book in which he argues that the key to the Industrial Revolution is that people in Britain started to believe that progress was possible and therefore started to be alert to, and actively create, ways to make progress happen (until the book arrives, see Howes 2017). David Wootton argues that before the voyages of discovery, intellectuals believed that history repeated itself and all knowledge could be found in the ancients. After the voyages many intellectuals began to believe that new discovery was possible and desirable in domains of knowledge besides geography. Wooton illustrates with a 1575 passage from Louis LeRoy:

"[T]here remayne more thinges to be sought out, then are alreadie invented, and founde. And let us not be so simple, as to attribute so much unto the Auncients, that wee beleeve that they have knowen all, and said all; without leaving anything to be said, by those that should come after them . . . Let us not thinke that nature hath given them all her good gifts, that she might be barren in time to come: . . . How many [secrets of nature] have bin first knowen and found out in this age? I say, new lands, new seas, new formes of men, maners, lawes, and customes; new diseases, and new remedies; new waies of the Heaven, and of the Ocean, never before found out; and new starres seen? yea, and how many remaine to be knowen by our posteritie? That which is now hidden, with time will come to light; and our successours will wonder that wee were ignorant of them" (LeRoy as quoted in Wootton 2015, p. 62).

[33] Melissa Schilling has argued that the desire to nurture children detracts from the intensity of female scientists, reducing their ability to be serial innovators (Schilling 2018b). She suggests that our institutions would make better use of scientific talent if they allowed scientists who have a break in productivity (for children or other reasons)

to have a later second chance to compete for the time and resources needed for scientific achievement.

[34] "The word "MACINTOSH" scrolled horizontally onscreen, then underneath it the words "Insanely great" appeared in script, as if being slowly written by hand. Not used to such beautiful graphic displays, the audience quieted for a moment. A few gasps could be heard" (Isaacson 2011, p. 169).

[35] "Jobs began pushing for a portable music player in the fall of 2000, but Rubinstein responded that the necessary components were not available yet. He asked Jobs to wait" (Isaacson 2011, p. 384).

[36] Jeff Bezos also "was a childhood addict of science fiction" (Isaacson 2023, p. 224). So too, inventor and futurist Ray Kurzweil was partly inspired to pursue his early life of invention by reading Tom Swift Jr. science fiction books as a child (Diamandis and Kotler 2012, p. 52).

[37] Cooper has retracted a story that he once told of being inspired by the flip communicator from the original *Star Trek* series (Hrdy and Brean forthcoming 2026).

[38] I have seen, but have not had time to confirm or refute, the following additional claims for science fiction inspiring new technology. Robert H. Goddard was inspired to build the first liquid-fueled rocket by reading H.G. Wells's *War of the Worlds* (1878). Jack Cover was inspired to invent the TASER stun gun by reading Edward Stratemeyer's *Tom Swift and His Electric Rifle* (1911). [The author is usually identified as "Victor Appleton," which is a pseudonym. Edward Stratemeyer outlined the plot and then hired a ghostwriter to fill in the details.] Konstantin Tsiolkovsky was inspired to develop his rocket equation by reading Jules Verne's *From the Earth to the Moon*

(1873). Jeff Bezos was inspired to found Blue Origin by reading science fiction authors including Issac Asimov and watching *Star Trek*. Igor Sikorsky was inspired to invent the helicopter by reading Jules Verne's *The Clipper of the Clouds (aka Robur the Conqueror)* (1887). The engineers who invented the MRI were inspired by the medical scanner in *Star Trek*. A naval officer was inspired to develop combat information centers by reading E.E. Doc Smith's Lensmen novels. Other potential, but not fully documented, examples of science fiction technologies inspiring eventually real technologies can be found on the web site Technovelgy.com.

[39] Besides firefighters and nurses, Gary Klein and his fellow NDM researchers also have studied decision-making by business managers, police, physicians, and pilots, among others. But as far as I am aware, they have not yet applied NDM methods to the study of inventors and entrepreneurs.

[40] Klein originally hypothesized that decision makers would compile two or more alternative potential decisions and then compare them. But he was surprised to discover that this was rarely the case. As a result, his research has led him to doubt the usefulness of some of the systematic decision strategies taught in MBA programs (Klein 2017, pp. 163-164 and 215-216).

[41] Joseph Schumpeter was another advocate of case studies in one of his final papers (Schumpeter 1947). Nobel-Prize-winner Ronald Coase made the case for case studies by doing them so well. See, e.g., his "The Lighthouse in Economics" (1974).

[42] The quote from Darwin supported Marshall's application of the mathematics of calculus to economics, since the calculus is the appropriate mathematics of marginal or incremental changes. Whether Darwin's quote is true of evolution is still debated.

Stephen Jay Gould and Niles Eldredge (Eldredge and Gould 1972) made a credible case with their punctuated equilibrium theory that nature *does* indeed make leaps. And mathematical models can be devised that imply such leaps. But the great accumulation of new fossils in certain periods, and not others, may be due to punctuated equilibria, or alternatively may be due to the limitations of what fossils we have so far discovered.

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