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Economists versus engineers: Two approaches to environmental problems

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Abstract
There are two distinct and partly irreconcilable approaches to analyzing environmental problems. The first, we call the engineering approach and the other the economic approach. The engineering view brings focus to the technical limitations we face in given production processes operating under given parameters. The economic approach brings attention on the crucial role of economic –and not simply technical– substitution and to the conditions under which humans successfully coordinate their plans. Environmentalists generally give weight to the engineering approach according to which substitution is too limited to enable durable economic growth. This hypothesis has empirical content. The available empirical evidence, however, vindicates the economic approach. At least in the case of raw materials, the expenditure shares used to pay for them have steadily declined since at least a century, suggesting that substitution is a powerful force and that their declining physical stock are getting less, not more, important for long run economic growth. Finally, we explain how the economic approach is unique in its emphasis on adaptation and the institutions under which adaptation is facilitated.

Keywords Environment · Human Progress · Adaptation · Julian Simon

JEL Classification N50 · O13 · O44 · B53

> The inherent misconception of [the environmentalist] interpretation is that it looks upon geography as an active and upon human action as a passive factor.

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> [...] [Geography] provides a stimulus but not the response. Geography sets a task, but man has to solve it.
>
> Ludwig von Mises, *Theory and History*.

1 Introduction

Julian Simon was among the first to confront environmentalists both on empirical and conceptual and theoretical grounds. On empirical grounds, he showed that predictions made by environmentalists were, time and time again, wrong. On conceptual and theoretical grounds, he tried to force them to recognize that the pessimistic view with respect to the environment presupposed omitting the most crucial resource humans have and develop: ingenuity.

Despite the obvious success of Simon's case, many remain unconvinced. In a 2009 interview, Julian Simon's long time rival, Paul Paul R. Ehrlich (2009), argued that *The Population Bomb*, in which he predicted irremediable mass starvation in the 1970's "was a ridiculously optimistic book." In 2017, in another interview, Paul R. Ehrlich (2017) claimed that "Everywhere we look, things are moving rapidly in the wrong direction. More rapidly than the scientific community originally expected. […] [Our] society is doomed." To many, natural resources will necessarily run out, population growth will lead to lower living standards, climate change will doom humans to worst living conditions and biodiversity will decline as economic growth continues. To some, degrowth is "an inevitable hypothesis," (Kallis, 2011) and to others, growth must be made "sustainable" through extensive government involvement in the economy or by limiting economic growth.

In this paper, we argue that there are two distinct and irreconcilable ways to think about environmental problems. The first, the engineering approach, is more intuitive to most people and focuses on how limited material inputs translate into limited output. The second, the economic approach, is the most useful approach, but it is not intuitive to the layman. The economic approach focuses on how humans *adapt* and try to coordinate with each other in a changing world. The engineer assumes a given menu of choice which must be optimally managed. Economists, on the other hand, recognize that there are multiple potential menus of choices faced by individuals, and they will change in the face of new challenges.

At first, the difference between engineering and economics may seem obvious: economics deals with individual choice while engineering does not. Yet once a given production function with given technologies and a given utility function are postulated, finding the optimal allocation of resources is no different from the engineer trying to optimize the output of a machine under given parameters and inputs. When all possible rates of technical substitution and preferences are known, coordinating economic activity to maximize utility becomes a trivial task. Economics, however, *is not* about finding a hypothetical optimal allocation of existing resources. Economics is about analyzing how individuals coordinate their plans with each other and change their environment to foster their own, varied ends.[1] The importance of focus on adaptation rather than simply allocation was observed by Julian L. Simon (1989b, 472):

> Crusoe certainly had an economic problem in the sense that the production of goods and services- mainly from natural resources found in a natural state- was of extreme importance to him. But contrary to the portrayal in elementary economic texts, Crusoe did not primarily occupy himself with allocating scarce resources among various competing means to his ends. To be sure, he did make some important allocation decisions. But most of his thought went into the creation and adaptation of technology.

The key point is that trade-offs –or rates of substitution– are not given to agents operating in a complex economy. More specifically, they are not invariant to either the natural or the institutional environment within which agents operate. We do not know today what the "marginal rate of substitution" will be between two inputs ten years from now because the future involves adaptation to changing conditions. We do not know what consumer preferences will be in the future because new goods will be invented. Global warming will, for instance, induce entrepreneurs to find not yet known or identified, ways to deal with higher temperatures. More efficient air-conditioning will be created, entrepreneurs will innovate by building more energy efficient construction materials, technologies will be developed to make moving inland cheaper, seeds will be developed to enable crops to resist higher temperatures, etc. Population growth will give extra incentives for entrepreneurs to find new factors of production complementary to labor and thereby make it more productive. The fall in the existing supply of fossil fuel will give extra incentives to find substitutes to fossil fuel and fuel-economizing technologies.

Adaptation to new environmental conditions is hard to imagine and predict, especially in the presence of Knightian uncertainty. If it wasn't, the innovations resulting from them would already be known and would not really be innovations in the first place. Assuming that adaptation will not happen because it is hard to conceptualize precisely what it will be, however, is more unrealistic than providing a convincing explanation of the conditions under which innovation occurs. Analyzing environmental problems requires that both the visible effects and the effects which cannot be directly foreseen be taken into account. Economists are uniquely able to analyze the development of new innovations because they can analyze the incentives pushing humans to innovate without specific and detailed knowledge about the content of each future innovation.

[1] This is not to say that assuming given utility and production functions may not be useful to explain human behavior. It is indeed necessary to do so to come up with predictions about changes in human behavior and coordination. Yet the usefulness of such assumptions does not rely on whether entrepreneurs in the economy know their production or utility function, but whether their implications are confirmed by evidence which in turns depends on the conditions under which entrepreneurs make enough money to survive (Alchian 1950). It does not follow from making those assumptions that economists have the necessary knowledge to derive the optimal allocation of resources independently from the actual process within which the allocation of resources takes place (Cheung 1978).

The assumption behind environmental pessimism is that adaptation –i.e. substitution of our current productive and consumptive activities by other means mitigating the cost of environmental problems– is difficult and severely limited. This assumption, as we will explain in further detail, has empirical implications which should manifest themselves in the data. If the environmentalists are right, the relative price of natural resources should increase, the share of output used to pay for natural resources should increase and wages should decrease. The data, however, gives credence to the economic approach focusing on the prevalence of adaptation and substitution. The engineering way of thinking about environmental problems is not simply broken conceptually but empirically dubious.

2 The engineering approach versus the economic approach

Carl Menger in his *Principles of Economics* (1871) described the pre-conditions for an object to be an economic goods as follows: (1) the existence of at least one human end, (2) properties such that it is possible to bring that object into a causal connection with the satisfaction of human ends, (3) Human knowledge of such connection, and finally (4) command of the thing sufficient to direct it to the satisfaction of those ends.

None of the conditions 1, 3 or 4 depend directly on the external, or "natural" environment to man. Human ends are not strictly speaking human made. The relative importance given to them by agents is the product of human choice. Human knowledge *is* man made –i.e. the result of a deliberate choice. Finally, command over a resource, that is whether property rights are at least partially established, is the result of both human choice and human institutions. Hence, only the properties of objects (material and immaterial) which are given by "nature" do not depend on humans.[2]

In a world with multiple means being able to fulfill multiple ends and where causal connections between potential means and ends need to be discovered, the number of goods which are considered in human choice is not a given, and economic resources cannot be considered as "finite" in the sense that their amount cannot be increased. It may be that the quantity of coal on earth is fixed, but imagine that a new machine doubles the amount of consumer goods produced with one unit of coal. The fact that the physical quantity of coal on earth decreases year after year is irrelevant to the fact that the amount of *economic* resources which can be used in the production process has increased with the new machine. The relevant criteria for a good, then, isn't its physical quantity but the availability of the services provided by that good.

The way the economist and the engineer think about production and resources is fundamentally different, and many disagreements relative to environmental issues

[2] Even this, however, is misleading. Humans can subjectively "know" a causal connection which is objectively wrong without making acting on that objectively false knowledge irrational. In fact, in many cases, objectively false believes are welfare improving (Leeson 2012).

stem from the inability to adequately acknowledge the different ways of thinking. The engineer is concerned with achieving a single end, such as maximizing the output of a machine, with quantities of productive factors –or their prices– being "given." Hence the engineer can, at least in principle, determine the best way to optimize the process he is concerned with in his mind even before he starts building the process in question. In the process he optimizes, the only way for production to increase is to build more of the same machine and use more of the same inputs. As Hayek (1944, 34) puts it, "The engineer […] has complete control of the particular little world with which he is concerned, surveys it in all its relevant aspects and has to deal only with 'known quantities.'" In that world, substitution, although not non-existent, is strictly limited and relates only to the given productive apparatus which needs to be optimized.

Economic resources and preferences are not the same as the objective data the engineer can rely on to execute his plans. Raw materials help the operation of the economy only to the extent that they and their uses are known to the relevant members coordinating their activities with each other. Crude oil before the age of the automobile was not a natural resource and was even, in certain circumstances, a nuisance. Neither are economic resources "material." With the invention of the radio, for instance, the electromagnetic spectrum became an economic resource the same way petroleum was an economic resource. The fact the spectrum is not "material" is irrelevant to its status as an economic resource contributing to the improvement of human welfare.

Economists think about the environment in different terms. The environment is relevant insofar as it impacts individuals. For example, individuals do not experience average temperatures. By modifying their environment through temperature control, damming rising waters, irrigating, and even simply relocating, human beings can modify the aspects of the climate they experience. As such, the economic approach involves viewing environmental problems as problems of adaptation to different conditions.[3] If adaptation to a new environment was costless, there would be no environmental problem at all.

By considering the economy as akin to a machine or a well thought plan, engineers do not take ends as given, they do worse, they take the ends as "frozen," meaning that they do not analyze human choice between multiple alternative ends and focus instead on technical substitution in the fulfillment of a single, well-defined, end.

In that sense, the task of the entrepreneur is wholly different from that of the engineer. The entrepreneur is not worried with the achievement of the ultimate end of the process he is involved in but is instead interested in making the best use of the means available and known to him. The process the entrepreneur is

[3] For instance, Desmet et al. (2018) estimate that "When ignoring the dynamic response of investment and migration [to flooding due to rising sea levels], the loss in real GDP in 2200 increases from 0.11 percent to 4.5 percent." Kahn and Zhao (2018) argue that climate skeptic may in fact slow down adaptation and therefore increase the cost of climate change. On the crucial role of economic adaptation for responding to climate change, see: Auffhammer and Kahn (2018). S. E. Anderson et al. (2019) and Kahn (2015).

involved in does not have a final end it must achieve. Instead, its role is to satisfy the most valued but not yet satisfied ends of his consumers, whatever those ends may be.[4]

Contrast the economic view to the one expounded in *The Limits of Growth: The 30-year update* in which it is written that "markets and technologies are merely tools that serve the goals, the ethics, and the time horizons of the society as a whole." (p.223–244). Of course, the market will adapt to individuals' demands. But seeing the market as a tool is misleading. A tool has a well defined function. The market does not. In the market, most of the end results are not deliberately sought but rather discovered and stumbled upon. The benefits of the market consist more in changing the menu of choice than optimizing a pre-existing and fixed menu of choice.

3 Substitution

(Mises, 1949), in his work on economic calculation, emphasizes that it is because the reallocation of resources changes the many marginal rate of technical substitutions between factors of production that central planners are not able to rationally allocate resources. In other words, the central planner is not able to use the current substitution ratios as "given" –that is as a basis for planning– because the reallocation of resources itself changes those ratios which have to be rediscovered anew by entrepreneurs.

In a modern economy, with hundreds of thousands of stages of production, it is impossible to make detailed judgments about the way production can be efficiently organized without the help of the market system. Yet this does not mean pattern predictions about adaptation and innovations cannot be formulated. Only the specifics remain unknown.

The implicit assumption behind the worry that the reduced geological availability of raw material will lead to an economic collapse is that it is hard to substitute such materials –for instance fossil fuel– by other means. For instance Lindsey Grant attacked Julian Simon and his "faith in infinite substitutability that Simon probably acquired from the academic economists. The assumption is not based on any systematic rationale, nor is it buttressed by any evidence…Biologists and ecologists have been trying without success to persuade the economists that the assumption is terribly dangerous in a finite world…" To which Simon replied that he did not "say that 'infinite substitutability' is possible now or at any future moment. What I do say is that substitutability is increasing with the passage of time; there have been more and cheaper substitutes for each raw material with the passage of time." (Julian Lincoln Simon, 1998)

[4] As Hayek (1944, 37) puts it, "The knowledge of when a particular material or machine can be most effectively used or where they can be most quickly or cheaply obtained is quite as important for the solution of a particular task as the knowledge of what is the best material or machine for the purpose. The former kind of knowledge has little to do with the permanent properties of classes of things which the engineer studies, but is knowledge of -a particular human situation.".

To contrast the Simonian from the prevailing environmentalist perspective, we can use the concept of the elasticity of substitution, which is "a measure of the ease with which the varying factor can be substituted for others" (Hicks, 1932, 117).[5] More precisely, the elasticity of substitution (σ) is defined as the percentage change in the ratio of the amounts of the factors engaged in production divided by the percentage change in the ratio of their marginal physical productivities –or prices under competitive conditions. Imagine an economy with two productive factors, labor (L) and a non-reproducible resource (R) –such as fossil-fuel. Then the elasticity of substitution is equal to:

$$\sigma = \frac{d\left[log(L/R)\right]}{d\left[log\left(P_R/P_L\right)\right]} \tag{1}$$

where P_R is the price of the non-reproducible resource and P_L the price of labor. From equation [eq:1], it is possible to show that as long as production follows constant returns to scale[6]:

$$\sigma = -\frac{d\left[log(R/Y)\right]}{d\left[log\left(P_R\right)\right]} \tag{2}$$

where Y is total output. Environmentalists assume that the elasticity of substitution between, for instance, fossil fuel and other factors is low.[7] In other words, the implicit assumption is that the demand curve for fossil fuel is inelastic and that a fall in the supply of fossil fuel will require a large increase in the quantity of other factors if production is to remain at the same level (Nordhaus, 1992). When the elasticity of substitution is lower than unity, the share of output paying for the factor of production becoming relatively scarcer increases.[8]

Figure 1 shows graphically the relationship between the elasticity of substitution and the output share for a non-reproducible resource R. The share of output used to pay that resource is equal to $\frac{P_R R}{Y}$. If the supply of the non-reproducible resource is falling from R^* to R' and the elasticity of substitution is high, prices will increase along the σ_{high} curve to P_h such that the output share of R falls ($P^* E^* R^* O > P_h E_h R' O$). If the elasticity of substitution is low, on the other hand, the fall in the supply of R will

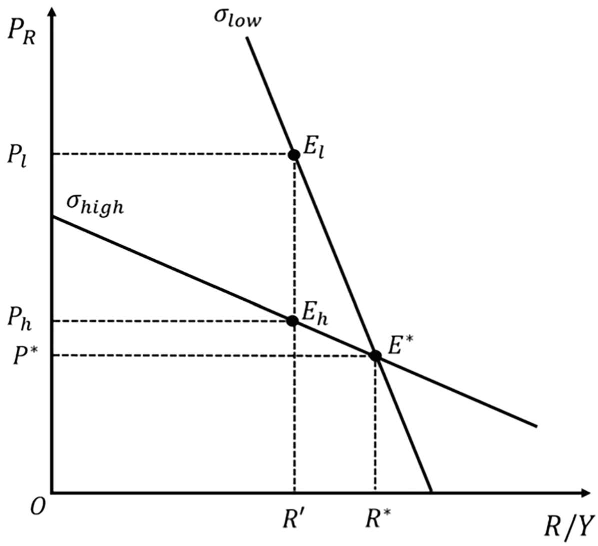
5 Not all environmentalists reject the Simonian or economic approach. See for instance T. L. Anderson and Leal (2001).

6 The proof is communicable upon request.

7 "Ecologists express concerns that natural resources have only a limited set of substitutes. They fear that to the extent that economists are overly optimistic about opportunities to substitute other capital assets for certain natural resources, reductions in their stocks would then receive too little weight." (Arrow et al., 2004).

8 Showing this is straightforward. With two factors, labor L and raw materials R, the relative share of the two factors is equal to $S = \frac{P_R R}{P_L L}$ where P_L is the price of labor and P_R the price of raw materials. Differentiating the relative share of raw materials with respect to the relative supply of raw materials R/L, we get: $\frac{\partial S}{\partial(R/L)} = \frac{P_R}{P_L}\left(1 - \frac{1}{\sigma}\right)$, where the elasticity of substitution is $\sigma = \frac{\partial(R/L)}{\partial P_L/P_R}\frac{P_L/P_R}{R/L}$. If $\sigma > 1$, a decrease in the relative supply of raw materials leads to a decrease its relative income share $\frac{P_R R}{P_L L}$.

Fig. 1 The Elasticity of Substitution and the Output Share.



trigger a much greater increase in the price of that resource and the share of output used to pay for it will increase.

With only few opportunities for substitution, a lower stock of natural resources would lead to an increase in their price which would be greater than the decrease in their supplies. Consequently, when substitution is difficult, an ever growing share of productive factors are allocated toward finding and mining non-reproducible raw materials. Surely if substitution of non-reproducible resources is difficult and that their finiteness is a problem, we should expect expenses made on them to rise over time. Evidence to the contrary is evidence against the view that humans are doomed by the finite amount of raw materials on earth.

Figure 2 shows the share of output used to pay for energy raw materials.[9] Contrary to what is sometimes believed, the process of economic growth since 1900 did not lead to a growing reliance on raw materials used to produce energy. Once we account for the use of fuelwood and horsefeed, which used to be of primordial importance for the production of transportation services and heating, the expenditure share used to pay for energy *decreased* by more than twofold in less than a century.

The decline in the output share used to pay for the dirtiest fossil fuel, coal, is even more dramatic, falling from more than 4% of GDP to around 0.1% of GDP in a century (Fig. 3).[10] Similarly, the expenditure share on fossil fuel has not increased since the 1970's and 80's. If anything, there seems to be a downward trend interrupted by temporary increases in the price of oil, especially in the 1970's and 80's as well as during the pre-2008 economic boom.

9 The data on prices and quantities of energy materials are given by Spencer (1980). The data on US GDP used is from Johnston and Williamson (2008).

10 The data used for Fig. 3 comes from Spencer (1980) (census) and the Energy Information Administration as well as from Johnston and Williamson (2008).

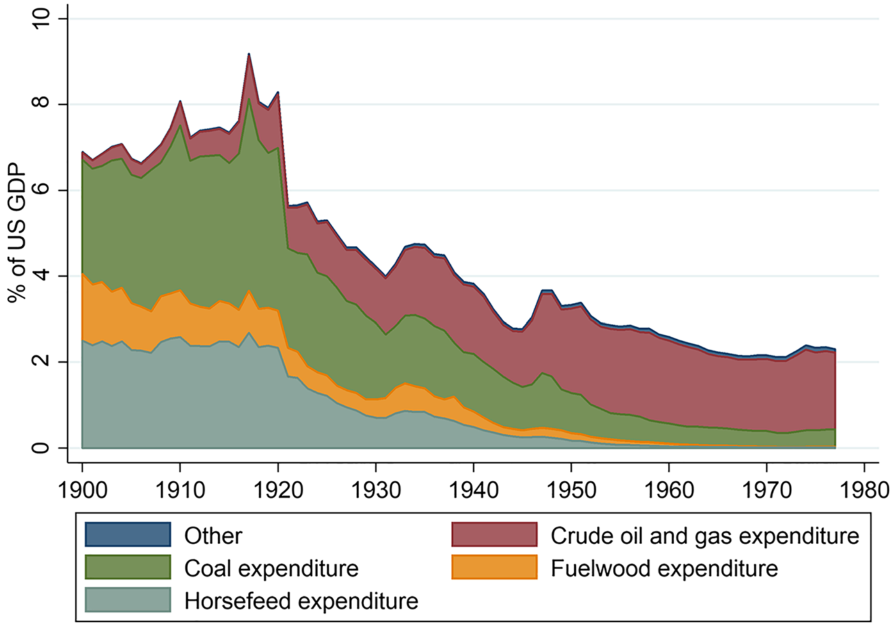


Fig. 2 Energy Raw Material Expenditures in % of GDP.

Julian Simon argued, contrary to many environmentalists, that the power of human ingenuity and the never ending pursuit for new substitutes will lead to a decrease in the price of raw materials. His argument and conjecture is a good one against the "we will run out of resources" view, but it is actually unnecessarily restrictive. Prices of raw materials could go up at the same time that the fall in the supply of raw material becomes less important for long run economic growth. That is as long as substitution of raw materials by other productive factors is easy enough, raw materials will represent a decreasing fraction of the economy, thus limiting the impact of a further fall in the supply of raw materials on growth. Since Julian

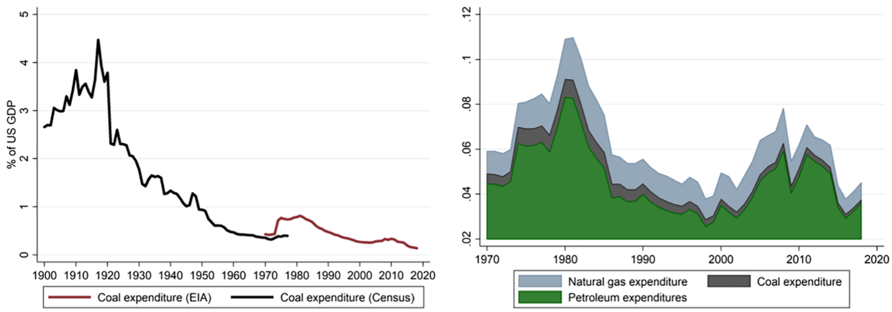
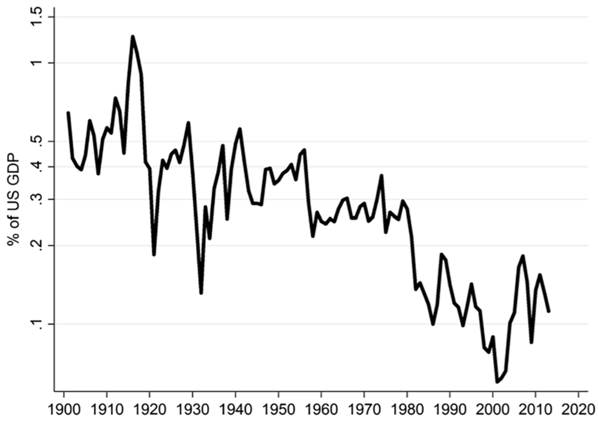


Fig. 3 Coal Expenditure and Expenditures on Fossil Fuel in % of US GDP.

Fig. 4 Expenditure on Commodities Included in the Bet Between Simon and Ehrlich (% of GDP).



Simon's conclusion is, above all, based on optimism about continued human progress, focusing on output shares is more adequate.

Indeed, the fact that the elasticity of substitution for so-called "natural" resources seems to be greater than one has an important implication: the lower the supply of natural resources, the less the scarcity of natural resources limits growth. Another implication is that when technological progress increases the marginal productivity of capital, labor and other factors relative to the marginal productivity of natural resources, the relative importance of natural resources will decline. But even in the absence of technological progress, high elasticities of substitution, if realized, risk making those favoring degrowth obsolete.

A number of environmentalists are also worried that "international competition for natural gas deposits may well parallel that of oil, where declining supplies are predicted, along with other energy resource shortages, to increase unrest and fuel wars in the near future." (Paul R. Ehrlich, Ehrlich, and Ehrlich 2008, 353). But here too, that worry is misplaced if expenditure shares on raw materials are declining, which indicates that such resources are becoming less, not more, important to sustain long term economic growth. Surely, war has been used for millennia as a means to appropriate economic resources, whatever those are. But to argue that the falling physical stocks of raw materials in the earth's crust is increasing the likelihood of war may be the opposite of what is likely to be true as predicted by Julian L. Simon (1989a). In fact, the recent rising tensions between the US and China has much to do with the stealing of intellectual property rights and industrial espionage instead of natural resources. In this sense, the tensions between China and the US vindicates Julian Simon's theory that *ideas*, not raw materials, are the ultimate resource.

Declining output shares signaling a high capacity for humans to substitute is not restricted to fossil-fuels. In 1980, after Ehrlich's claim that he'd bet England wouldn't be a country by the year 2000, Simon challenged him to a more reasonable bet. They bet that a bundle of five metals (chromium, copper, nickel, tin, and tungsten) would fall over 10 years. In 1990, Ehrlich mailed a check of $ 576.07, confirming Simon's win (Regis 1997).[11] Somewhat ironically, the output shares

[11] Ehrlich and Stephen Schneider later offered a counter-bet which Simon refused, though Desrochers, Geloso, and Szurmak (2021a, 2021b) argue that even the outcomes of this bet would vindicate Simon.

used to pay for the commodities included in Julian Simon's 1980 bet against Paul Ehrlich have declined steadily for more than a century (Fig. 4).

Contrast the stylized facts presented above with what the authors of *The Limits of Growth: The 30-year update*:

> If only one or a few resource stocks were falling while others were stable or rising, one might argue that traditional growth could continue by the substitution of one resource for another (though there are limits to such substitution). If only a few sinks were filling, humanity might substitute one (say, the ocean) for another (say, the air). But since many sinks are filling and many stocks are declining, and the human ecological footprint has surpassed the sustainable level, we need a more fundamental change. (p.122)

Is substitution close to impossible because the stocks of raw materials we use are all shrinking? No. First, substitution of raw material intensive goods by other goods is possible. Second, as we mentioned earlier, economic resources are objects (physical or not) which we know how to use to satisfy our ends. Yet many potential resources are still unknown. Substitution is not only substitution between existing resources but also substitution of known resources by not yet known resources. In other words, substitution is dynamic. Third, if substitution was close to impossible, we would not see expenditure shares on raw materials decreasing.

Even when ample opportunities to substitute non reproducible resources with reproducible ones exist, however, we should expect, in the absence of technological change, the relative price of natural resources to increase through time. A fall in the relative price of natural resources is evidence of technological change biased *against* "natural" resources, that is of technological change increasing the marginal productivity of other productive factors by more than that of "natural" resources. We now turn our attention to how market prices provide opportunities for entrepreneurs to adapt by expanding the number of available substitutes and by improving current production processes.

3.1 The role of prices

One interpretation of Hayek (1937, 1945)'s work on prices and knowledge is that prices *communicate* decentralized, but already discovered, information, thus enabling market participants to act as efficiently as possible. Although this is indeed something Hayek argued, Hayek also argued that prices offer opportunities for market actors to *generate* and process new and previously unimagined knowledge by the very fact of facing new circumstances and making new mistakes (Kirzner, 1984). The role of prices for environmental adaptation is not only one in which pre-existing knowledge is communicated as efficiently as possible. Price movements and market phenomena also lead entrepreneurs to face and solve previously unknown challenges and stumble on new ideas about how to adapt to new environmental conditions.

The "engineering" approach to environmental problems, on the other hand, generally relies on reduced form relationships between the environment and individual actions and omit the dynamic effect of price changes. An example of such reduced form relationships is that between temperature and GDP or between the price of oil and GDP. From these reduced form relationships, quantitative predictions about future conditions are formulated.[12]

Yet, given the dynamic nature of the market process, current statistical relationships between economic and environmental variables have next to no relevance to the magnitude of those relationships in the future. The reason is that humans create new tools instead of relying only on the current means available to them for adaptation. When "Mother nature" changes the rules of the game, the relationship between economic activity and environmental variables also changes because individuals readjust their plans to newly expected conditions. Putting this in economic jargon, analyses of environmental problems often suffer from the Lucas critique (Kahn, 2015).

A researcher may look at the relationship between daily temperatures and annual mortality rates or daily temperatures and annual residential energy consumption to estimate, by extrapolation, the cost of climate change under "business as usual" assumptions (Deschênes & Greenstone, 2011). Yet such estimations are completely misleading: humans will not passively continue to live their lives as temperatures increase. For instance Barreca et al. (2016) found that during the twentieth century "the mortality impact of days with mean temperature exceeding 80F declined by 75 percent." especially due to the introduction of air conditioning. In other words, relationships between environmental variables and human behavior is non stationary and the cost of environmental problems can be estimated only after accounting for adaptation. Problems breed solutions.

Most studies estimating the environmental impact of human activity fail to account for adaptation and do not rely on "structural environmental parameters." For instance "most existing literature quantifies the impact of climate change on economic outcomes based on estimates of short-run response." (Chen & Gong, 2021, 12).[13]

Another example of misleading estimation relates to "natural" resources such as metals, fuel or water. Further Julian Lincoln Simon (1998, 25, p.126–169, p.151–153) showed that most predictions about the exhaustion of those resources were completely false precisely because, somewhat paradoxically, their falling physical stock channels the human mind toward finding new ways to make those resources less scarce. To this day, however, Julian Simon seems to have failed to

[12] Tol (2009), in his survey on the economic damage of climate change distinguishes between two estimation approaches –both of which fail to account for the role of dynamic adaptation. The first, the statistical approach "is based on direct estimates of the welfare impacts, using observed variations (across space within a single country) in prices and expenditures to discern the effect of climate. [It] *assumes that the observed variation of economic activity with climate over space holds over time as well*; and uses climate models to estimate the future effect of climate change." [emphasis added].

The second, the enumerative approach, "estimates of the "physical effects" of climate change are obtained one by one from natural science papers […]. The physical impacts must then each be given a price and added up. For agricultural products, an example of a traded good or service, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value the change in output." As Tol (2009) recognizes, "the enumerative approach also has […] concerns about extrapolation: economic values estimated for other issues are applied to climate change concerns; values estimated for a limited number of locations are extrapolated to the world; and values estimated for the recent past are extrapolated to the remote future.".

[13] For instance, Deschênes and Greenstone (2007). On the role of adaptation to climate change in the agricultural sector, see: Auffhammer and Kahn (2018).

convince ecologists of the crucial role human ingenuity plays in reducing the scarcity of so-called natural resources.

For instance recent studies estimating water shortages or consumption completely fail to account for the role of *economic* adaptation. Brown et al. (2013), Blanc et al. (2014) and Brown et al. (2019) estimate future water demand without any reference to water prices or price induced innovations. As Brown et al. (2019) puts it, "future demands were estimated assuming that future supplies will be much like recent past supplies." while in Blanc et al. (2014), they are estimated "based on recent experience and therefore implicitly assume current or recent prices." Surely, evaluating future shortages without reference to likely price changes is, to put it plainly, nonsense. The engineering approach, by assuming given ends, given means, and fixed relationships between ends and means, overstates by construct the magnitude of environmental problems.

The economic approach, on the other hand, recognize that as the environment changes, so will prices. Those price changes will not simply communicate knowledge about the underlying supplies of land, water, fossil fuel, food as well as the underlying risks of natural disasters. Those price changes will also trigger dynamic responses generating new useful knowledge aimed at solving environmental conundra.

Take the instance of a rise in the price of fossil fuel. Entrepreneurs have a choice between creating either new innovative complements to fossil fuel or new innovative substitutes to fossil fuel.[14] The demand for complements/substitutes to a resource decreases/increases in its price. The same logic applies to innovative complements or substitutes. Hence the increase in the price of fossil fuel triggers a discovery process aimed at finding new substitutes to that resource.[15]

When fossil fuel was first discovered and made available in large quantities, the increase in its extraction gave an impetus for entrepreneurs to find new complements to fossil-fuel, thus increasing the value of that resource. This was the period where cars and planes were developed. When fossil fuel becomes more difficult to extract, on the other hand, finding substitutes to fossil fuel becomes relatively more profitable.

Assuming the physical stock of non-reproducible fossil fuel is shrinking, innovations to improve the processing and utilisation of fuel tends to fall as well. Demand for this kind of technological change will be greater when fuel is more abundant. On the other hand, the demand for innovations providing substitutes to fossil fuel does not suffer from the same problem. A fall in the supply of fossil

[14] Acemoglu (2002) develops a model of directed technological change in which innovations are physical complements to any one factor of production –i.e. they increase the physical productivity of one factor. Innovations, in his framework, are substitutes to a productive factor only if they augment another productive factor which is also a substitute to that first one. It does not allow for the creation of completely new factors which do not directly change the physical productivity of existing factors of production, but which nonetheless serve as substitutes to some of them. Using the broader distinction between innovative substitutes and innovative complements, on the other hand, allows to analyze the development of those kinds of innovations.

[15] Popp (2002) finds that the short and long run elasticities of energy patents with respect to energy prices are 0.125 and 0.625 respectively.

fuel increases the demand for creating electric or hydrogen cars relative to the demand for improving thermic engines. As long as the substitutability of dirty and exhaustible by clean fuel is high, the decline in the physical stock of "dirty fuel" will give extra incentives for entrepreneurs to improve "clean fuel" technology while the incentive to improve "dirty fuel" intensive production processes will decrease (Acemoglu et al., 2012). Indeed, why invest in improving production processes using "dirty fuel" when the market share of "dirty fuel" is falling over time? Thus the market, to the extent it offers many opportunities to both use and discover substitutes, takes care of the energy transition by itself, even without proactive government policies.[16]

The same logic applies to one of Julian Simon's favorite topics: population growth (Julian L. Simon, 1977, 1986, 1990). As population grows, so will the labor supply, which means that workers will command, in the short run, a lower wage. A falling wage will trigger a discovery process aimed at developing innovative complements to labor. In turn, those complements will increase wages.[17]

Notice that the economist's focus on *economic* substitutes is completely different from the engineer's focus on *technical* substitutes. For the economist, the same innovation can be an economic complement to a resource in certain contexts and an economic substitute to the same resource in others. Take the example of a new motor engine dividing gas consumption per millage by two. If the demand for driving is inelastic with respect to gasoline costs, an increase in the supply of the new motor engine will decrease demand for gasoline while it would increase it if the demand for driving was elastic. In other words, the invention of the new engine is a substitute to gasoline when demand for driving is inelastic and a complement when it is elastic.

In Fig. 5, we use the relationship between the relative demand of gasoline and its inflation adjusted price to exemplify our point about the non-stationarity of relationships related to environmental resources and variables.[18] To mirror the discussion in Sect. 3 (and especially Eq. 2) on the elasticity of substitution, we log our variables so that slopes represent elasticities.

Inspecting Fig. 5, it seems that there are two distinct negative relationships, as predicted by the law of demand, between the relative demand for gasoline and its price. We added lines of best fit for the first (1970 to 1982) and second (1998 to 2014) periods. High prices in the early 1980's seems to have led to a two-decades-long, persistent fall in the relative demand for gasoline.

[16] Worries about running out of fossil fuel and pessimism about pollution related to fossil fuel are not fully consistent. If fossil fuel is a non-reproducible resource whose stock is rapidly declining, one should be optimistic that pollution related to the exploitation of fossil fuel will also rapidly decline.

[17] Inversely, Habakukk (1962) argues that labor scarcity during the nineteenth century "gave the American entrepreneur with a given capital a greater inducement that his British counterpart to replace labour by machines.".

[18] The data can be found at: U.S. Energy information administration, Table 3.7c Petroleum Consumption: Transportation and Electric Power Sectors and Table 9.4 Retail motor gasoline and on-highway diesel fuel prices (Accessed on 3/1/2021). Data on real GDP and the GDP deflator (to calculate real gasoline prices) are from the BEA.

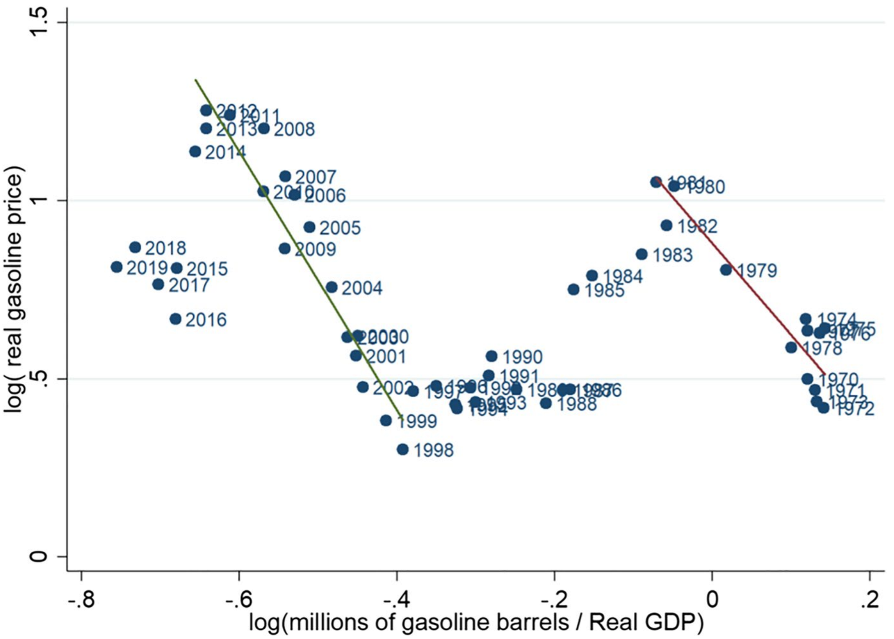


Fig. 5 The Relationship Between Gasoline Used Per Dollar of GDP and Real Gasoline Prices.

As we have explained, prices are a powerful engine for adaptation, especially through knowledge generation. But when substitution occurs mostly through new innovative products developed after price movements, measures of long-run elasticities may be biased downward. For instance the 1981 oil shock led to what appears as a permanent fall in the demand curve for gasoline. New more energy efficient engines were created. Yet once those innovations are discovered, they will be available whether or not oil prices go back down. The period of low gasoline prices in the 1990's was much longer than the period of relatively high prices in the beginning of the 1980's, yet the short-run relative demand for gasoline did not increase back to its original level and even continued to fall. Similarly, the period of high gasoline prices after the 2008 financial crisis seem to have led to another downward shift in the demand curve for gasoline although it is too early to say. Overall, the data in Fig. 5 provides some suggestive evidence about how adaptation to changing market conditions can persistently alleviate resource scarcity.

Of course, we can never be certain that technical progress and adaptation will continue in the future. But neither can we be certain that it won't –an assumption which sounds much less plausible. It is also true that estimating the magnitude of environmental problems, whether it be climate change or depletion of natural resources, suffers from insurmountable knowledge problems as we do not know, for the most part, how those environmental problems will manifest themselves nor what kind of adaptation will be implemented in response to them. As we have explained earlier, most empirical estimations of environmental problems use the engineering instead of the economic approach by relying on reduced form statistical relationships which suffer from the Lucas critique. In other words, those statistical relationships derived from historical data –between temperature and GDP or between the price of oil and its consumption for instance– are not structural as they are not invariant to the overall state of the environment. Yet the “structural” parameters are difficult if not impossible to know when agents face genuine Knightian uncertainty –i.e. situations they have never encountered before and where the probability distribution of possible outcomes is therefore unknown.[19] Often, all we can hope to know is how likely certain institutions are to encourage adaptation to environmental problems without knowing in detail which problems will arise.

4 Institutions and adaptation

As previously discussed, the ability to adapt to changes in the climate or resource availability is influenced by the institutional context economic actors find themselves in. In Sect. 2, we discussed the theoretical shortcomings of the engineering approach to evaluating resource and environmental problems. In Sect. 3, we evaluated evidence and found support for the economic approach over the engineering approach. In this section, we will illustrate how the engineering view’s shortcomings can have unintended consequences in the realm of policy decision-making because the view deals with a fixed menu of choice and therefore excludes how institutional changes can affect how the menu of choice changes.

First, legislation risks "polluting" the adaptation process with rule changes which could hamper both the knowledge and the incentives associated with positive adaptation. Without access to prices, knowledge of the marginal rates of technological substitution will not be attainable. Second, a focus on first-best policy responses may be fruitless in the face of the interest group incentives which drive public policy. Political transaction costs may be such that optimal policy responses are outside of the opportunity set. Finally, even the potential for policy intervention may lead to rent-seeking adaptations on the part of special interest groups.

4.1 Polluting the knowledge creation process

As resources become more scarce, increased prices offer incentives from entrepreneurs to create technological substitutes among means (as Simon indicated) but also economic substitutes among ends. As such the inevitability of regulatory solutions to modern environmental problems is called into question.

[19] As Newell, Prest, and Sexton (2021) put it with respect to climate change, “[T]he econometric approach confronts two challenges in estimating aggregate economic impacts of climate change. First, identification of climate effects from weather variation requires strong assumptions about dynamic processes like adaptation and the persistence of idiosyncratic temperature responses amid secular climate change […]. Second, *theory does not prescribe specific, estimable, structural relationships between climate and economic outcomes.*” [Emphasis added].

However successful environmental regulation may be not only be unnecessary, but it may even harm the environment that proponents intend to protect. In other words, the means proposed by environmentalist engineers to solve environmental problems may harm the environment. This is because such policies alter institutions in such a way that it would make entrepreneurial discoveries likely to improve environmental quality more difficult to achieve (Boettke & Coyne, 2003). To understand why, we must bring the background institutions of our theory into the foreground.

The manner in which environmentalist policies pollute this process of adaption is relatively straightforward. In order to pursue the end of sustainability, policy engineers must support policies which give government authorities discretion over the extent to which natural resources can be exchanged. Assuming we grant the assumption of low elasticity of substitution of natural resources for sake of argument, it may be tempting for policy proposals in this vein to hypothesize some welfare function which attempts satisfy inter-generational utility. The problem with this approach is it assumes away the very problem it claims to solve. The political process is not a black box wherein policy proposals are inserted and outputs are generated in response. Replacing the competitive market process with the political process does not eliminate competition for scarce resources— it merely changes the form. And, in changing the form, knowledge generated by market prices cease to exist.

The role of prices in communicating knowledge about relative scarcities and offering incentives for solutions concerning changes in relative scarcity does not come about ex nihilo. Rather, prices emerge as the result of exchanges by individuals and thus require an institutional framework consistent with such behavior. An institutional framework which provides for clear and defined private property rights will enable environment-improving innovations to succeed. By allowing exchange over resources, prices will emerge which will provide knowledge about which resources are becoming more scarce. Simon (1998, p.98) recognized the role of prices in his grand theory of decreasing natural resource scarcity:

> More people, and increased income, cause problems of increased scarcity of resources in the short run. Heightened scarcity causes prices to rise. The higher prices present opportunity, and prompt inventors and entrepreneurs to search for solutions.

This process laid out by Simon requires the existence of prices to signal the increased desire for solutions to resource problems. As such, the process requires the institutions which generate such knowledge. Ludwig von Mises ([1920] 1975) makes clear that knowledge generation of this type is context-dependent. Without such signals, the process of innovation central to Simon's theory does not occur. As such, environmental regulations which attenuate the ownership of natural resources degrade the ability of entrepreneurs to solve environmental problems.

Further, as means-substituting and ends-substituting innovations are created, these prices play an important role in ex post accounting to determine if the technological improvements were valuable enough to warrant the resources used. As Simon (1998, p.98–99; emphasis added) also points out, "many [entrepreneurs] fail, *at cost to themselves*. But in a free society, solutions are eventually found."

Again, the ability of entrepreneurs to evaluate the costs for themselves does not fall from the sky. In order to account for the success or failure of a particular innovation, entrepreneurs must be able to utilize market prices. Political intervention which effects these prices, then, dampens the ability to gauge the success of solutions to environmental problems.

4.2 Adapting through rent-seeking

Kahn and Zhao (2018) argues that climate skeptics may slow down adaptation and therefore increase the cost of climate change. On the other hand, he argues that economists estimating reduced form relationships to estimate the cost of climate change improves the prospects for adaptation and therefore make the world a better place. That is true only in certain auspicious institutional environments, but econometricians estimating (misleading) reduced form relationships could also lead people to adapt on the wrong margins: pervasive rent-seeking, bureaucratization of environmental adaptation and over-politicization of the reaction to climate change. Not all adaptations are equal.

Whenever a policy is enacted, distortions (externalities) in the private market are not alone to be considered. Distortions (externalities) caused by such policies in the political market must also be accounted for. The same is true for estimating reduced form relationships between environmental and economic variables. Such estimations may help private sector adaptation on the one hand because it makes entrepreneurs aware that continuing “business-as-usual” will lead to major problems. On the other hand, the positive externality of producing such estimations may either be reinforced if leading to better policies or weakened if it incentivizes political agents to implement policies harmful to the economy and deterring market adaptation.

Consider, for example, the possibility that owners of stocks of fossil fuels also read the reduced form relationships produced by economists. An overly simplistic reduced form relationship which overestimates the harms of climate change by excluding the possibility of adaptation may inspire private actors to put more work into adaptation, but it’s also likely that, if these estimates can impact private decision-making, they will also impact public policies.

At first glance, this may seem like a positive result assuming the policies are aimed at correcting externalities. However, as observed by Sinn (2012), if the owners of fossil fuel stocks believe these reduced form relationship estimates will speed regulation on their ability to extract their stocks, we should expect extraction and its subsequent climate effects to accelerate. As future property rights over the resources becomes more uncertain, they will be extracted earlier.

The same logic can be applied to a perceived limited "stock" of some natural resource. If the owner of copper mines begins to suspect politicians will legislate limitations on how much can be extracted per year, it is in the owner’s best interest to increase copper production (and any attendant pollution) today. Otherwise, the firm will be required to forgo profits on all copper sales that would’ve been made absent the legislation.

While extraction speed will likely increase, there will be other margins of adjustment. One way to protect future property rights over a fossil fuel stock is to extract them today, but owners could also protect their future property rights by buying the property rights back. As the threat of climate change is made more apparent, the rents to capturing regulation of industries closely linked to climate change will increase. Adaptation through regulatory capture seems a likely response to this increase in rents.

The threat of increased regulation of fossil fuels won't only effect the rents available to suppliers. Regulations aimed at decreasing the demand for oil, such as a mileage tax on oil-powered cars, create rents for consumers who are able to lobby for special exemptions. As regulations decrease demand, those who are exempt will be able to enjoy the ability to consume oil at a lower price and will increase their consumption. If, for example, farmers were able to secure an exemption from this tax, it seems reasonable to expect agricultural special interest groups would be formed in response. Likewise, governments of countries which refuse to implement similar taxes or regulations would be incentivized to spend money to influence other countries to do so in order to enjoy lower prices and increase consumption. Reduced form estimates could accelerate these rent-seeking adaptations.

These considerations beg a deeper question the engineering approach must address before recommending optimal policy— are optimal policies in the opportunity set given the current political institutions? Assuming that discovering a policy that leads to improved social welfare will be implemented requires assuming that those in charge of of its implementation have an objective function which matches with the end of improving social welfare. However, there is no reason why this must be the case. Rather than assuming political institutions are a black box which seek to maximize social welfare, it is more consistent to consider these institutions to be made up of individual actors pursuing their own self-interest.

Implicit in the engineering mindset's solution of environmental problems is the assumption that individuals acting in the private sector will sometimes make decisions which conflict with social welfare. This is certainly true. However, this is no less true of politicians acting in the public sector. Consistency requires treating political actors the same as private actors. Such an assumption leads to very different conclusions and proposals. For example, it would seem strange to propose, as a solution to environmental problems, that we simply ask private interests to pursue social welfare rather than their own private interests. It is no less fruitless, then, to propose this suggestion to agents in public institutions.

For instance (Buchanan & Tullock, 1975) argue that Pigovian taxes such as carbon taxes are much less likely to prevail in environmental policy-making than command and control solutions. This is because command and control create concentrated benefits to special interest groups. However, a Pigouvian solution in the case of environmental regulation, provides no concentrated benefits. As such, we should expect even ideologically-motivated politicians to support policies that depart from a first-best Pigouvian tax if they wish to be successful. Politicians who refuse to engage in political exchanges will find themselves with relatively less support than those who don't. Yet as we have argued, command and control policies, by restricting the use of the price system, will reduce market adaptation.

The cost of potential rent-seeking isn't limited to the problem that it may put an imaginary optimal policy response out of the opportunity set. By capturing regulations, consumers and producers consume resources which could have been used in productive innovation. Further, by adapting through political innovation, the incentive for the invention of technological improvements falls.

If a special interest group is granted exception to regulatory policies on gasoline, the potential profit from discovering alternative cleaner energy will be lower. In the extreme case, such policies may even create interest groups which work against technological adaptation. An example of this may be homeowners in areas susceptible to floods and therefore lobbying for disaster relieve instead of improving construction or migrating.

By assuming first that the knowledge necessary for successful innovation exists independent of the institutional setting, and second that political decision-makers will have the incentive to work to bring about some maximized social welfare function, the engineering approach moves from simply being less theoretically and empirically convincing than the economic approach to being harmful to the ends it is aimed at.

5 Conclusion

It is of course true that we cannot be sure that the trends we observe in the past will continue in the future. Substituting current production processes by others as raw materials get scarcer may become harder. Innovations may become scarcer. Yet it does not follow that we should act, in the realm of policy making, as if humans will only face dead ends in face of the new environmental challenges. Surely, the assumption of no future innovation seems a lot more unlikely than that of continued adaptation. Julian Lincoln Simon (1998, 57) illustrates this with an example:

> We look at a tub of water and mark the water level. We assert that the quantity of water in the tub is "finite." Then we observe people dipping water out of the tub into buckets and taking them away. Yet when we re-examine the tub, lo and behold the water level is higher (analogous to the price being lower) than before. We believe that no one has reason to put water into the tub (as no one will put oil into an oil well), so we figure that some peculiar accident has occurred, one that is not likely to be repeated. But each time we return, the water level in the tub is higher than before - and water is selling at an ever cheaper price (as oil is). Yet we simply repeat over and over that the quantity of water must be finite and cannot continue to increase, and that's all there is to it.
>
> Would not a prudent person, after a long train of rises in the water level, conclude that perhaps the process may continue - and that it therefore makes sense to seek a reasonable explanation?

Our analysis has clear implications for future study of environmental problems. Rather than operate under a theoretically and empirically fraught engineering approach in dealing with environmental problems, economists would do best to follow Simon's lead in utilizing the economic approach. This approach calls for a focus on adaptation and the institutional incentives underlying adaptation rather than attempting to find the social welfare maximizing inter-generational allocation of resources. The market is above all an institution, not a set of optimization conditions.

Second, economists who wish to influence public and private adaptation should be aware how the institutional environment effects the way in which adaptation occurs. Adaptation can involve wealth creation, but individuals may also adapt through engaging in rent-seeking activities or by speeding up resource use.

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