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# Inventive processes in nature: from information origin in chemical evolution to technological exhaustion

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## Abstract

It has been ten years since the 2006 work of Abel and Trevors wherein the cybernetic path of life's origin was proposed as an alternative to the widely held views of such origin being self-ordering and self-organisation. Cybernetic adaptation is now recognised as a cornerstone of biological and technological evolution and as well as of artificial intelligence (AI) and cognition. It is expected that chemical evolution, preceding biological evolution, will have a cybernetic explanation as well. Among all evolutions, only AI evolutionary computation and cognition are accessible via the scientific method. For biological and technological evolutions, we only have the example of one, while for chemical evolution we have no template at all. The aim of this essay is to look for commonalities in all evolutions and attempt to fill in the missing pieces of the chemical and technological evolutions with knowledge that can be obtained by observing evolutions with a complete record. Types of information – quantum, chemical and functional – are defined, and their roles explained. It is proposed that the temporal survivability of information should be considered as a factor of general evolutionary fitness for all evolutionary adaptations. This study further suggests that because all experimentation spaces are finite they may become exhausted due to convergence towards optimal configurations. Such exhaustion of important experimental areas might reflect the observed decay of technological innovation and economic growth.

**Keywords:** Chemical evolution, Biological evolution, Technology, Innovation, Exergy, Evolutionary cybernetics

## Introduction

Invention is a search result that endures over a space of combinatorial possibilities, while innovation involves the replication and diffusion of inventions. Inventors have explored and tested potential ideas that might become inventions, which were subsequently retested on the market as replicated products and services (Kell and Lurie-Luke 2014). Scientists have long observed that technological innovation closely resembles biological evolution (Nelson and Winter 1982); moreover, ideas based on evolution have been introduced into computational artificial intelligence (AI) (Forrest 1993; Koza et al. 1999). AI, technological development, and evolution can all be considered creative processes within the universal Darwinism proposed by R. Dawkins (1983). These processes all generate, process, and test information for fitness (Bedau et al. 2000). When tested, this information faces oblivion. If identified as unfit, this information will eventually be forgotten and erased. Surviving information presents a new addition to the combinatorial space for further improvements, where experimentation provides for information reuse.

Currently, it is not well understood how these informational processes work in nature (Bedau et al. 2000). In particular, biology has not been able to adequately explain early evolution (Yockey 2005), where the period of prebiotic, chemical evolution is of particular interest. It is a prolific view that chaotic dissipative processes with observable criticality or known self-assembly or self-organising processes might have somehow played a part in chemical evolution. Abel and Trevors (Abel 2006) brought this view into question by pointing out the simple fact that entropy-generating dissipative processes destroy information and leave none behind after the driving force is removed. This is in stark contrast to processes of life where information is built up and even left behind after the driving force is removed. Abel and Trevors postulate that the origin of life must be

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cybernetic. The aim of this study is to provide sought cybernetic view of the processes of life through the description of inventive processes in nature.

Thermal disequilibrium is known to play a role in life processes. Its precise role from a cybernetics standpoint is to generate physical information. Christopher Jarzynski pioneered this field, which today is a prolific branch of physics called fluctuation theorems (Jarzynski 1997, 2011). The conversion of energy into physical information, combined with exploration processes from evolution and AI sciences, provides a plausible explanation for early inventive processes in nature (Ruelle 2017). Evolution and technological development likely evolved through stages of increasingly evolved exploration and exploitation mechanisms (Table 1). A 'noisy search' is proposed here as a mainstay of all exploration processes in nature. This process incorporates physical information generated or distorted by thermal disequilibrium noise into experiments within the environment. Therein, unfit information is lost through naturally present entropy-increasing events, and the remaining information becomes invention. Among the three currently recognised requirements for natural selection – variation, fitness differences, and replication with heredity (Griffiths and Gray 1994) — variation and fitness evaluation are fundamental. With the addition of energy disequilibrium as an information generator and mechanisms for information addition and diffusion, variation and fitness evaluation are sufficient for evolution to continue. The mechanism for information addition provides for the adaptation of biological and technological complexity. Such a view enables the question of primordial plausibility in the search for the origin of life to be overcome as it relies on informational mechanics rather than the exact chemical pathway, which may never be known. This change of view is significant and requires some time to be accepted by a reader used to dealing with specific chemicals.

## Inventive processes: the two pillars

### Pillar 1: Information origin

#### *Three levels of information: quantum, chemical, and functional*

Quantum information is thought to be universally conserved. A quantum of energy can only be transferred forward (Samal et al. 2011). A system about which nothing can be said contains no information. Three distinct levels of information can be identified regarding other systems. A paper document, a genome, and an optical cable, for example, carry functional information (Wright 1973; Landauer 1996; Jablonka 2002) relative to those who can evaluate it. Anything is a source of *functional* information if it has a range of possible states, and one variable carries information about another to the extent that their states are physically correlated (Godfrey-Smith and Sterelny 2016). At a step lower, there is information on the paper's chemical and physical configuration represented by free energy or configuration entropy. At an additional level lower, there is quantum information

**Table 1** Innovation milestones throughout the evolution of the Earth

| Physical information representation | Small organics | Polymers | RNA | DNA | DNA, neural, technological |
|---|---|---|---|---|---|
| Algorithm: | | | | | |
| Exploration method, Far search | Molecular noisy search | Molecular noisy search | Molecular noisy search, high frequency mutations | Low frequency mutations | Neural experimentation through neural noisy search, numerical mutation operators in AI |
| Exploitation method, Near search | None | Information addition (polymerisation), horizontal chemical information exchange | Old information addition (polymerisation) + horizontal gene transfer | Old information addition (polymerisation)<br><br>+ horizontal gene transfer<br>+ sexual information crossover | Thought experimentation, numerical crossover in AI |
| Invention diffusion method | Diffusion in liquid solvent | Parallel chemistry, solvent diffusion | Replication, solvent diffusion | Replication by heredity, solvent diffusion | Offspring, industrially manufactured copies |
| Dominant exergy source | Radiation (UV) + planetary dynamics | UV + some metabolic | UV + metabolic | UV + visible + metabolic | Metabolic (+ nuclear, solar…) |

From left to right, small organics primarily based on solar ultraviolet (UV) light and thermal noise are the first carriers of information concerning the first experimental outcomes. The next process, where previously stored information is added in small molecules, involves polymerisation or elongation. RNA is the next major evolutionary step in the information selection method. RNA facilitates horizontal gene transfer and replicates to diffuse information. After the appearance of metabolism, inventions tended to be oriented towards an increasingly elaborated protection schema. A great advance in horizontal information exchange was gained by the invention of sexual DNA reproduction by the systematic crossing of previously known inventions at reduced mutation rates and provided a mechanism against deleterious mutation accumulation (enabling reduced mutations). Moreover, within intelligent, neural beings, inventive processes have arguably ascended to another level, much more advanced than the solely genetic level, into a higher realm of thought experimentation. In humans, perhaps we see an even higher level evolved, that of consciously directed thought experiments regarding the underlying energy quanta and their arrangements (Zeilinger 2005). Information on the chemical configuration of the paper 'is encoded' as numerous metastable chemical states relative to the world in which the paper exists (Fig. 1). Here, 'world' should be viewed as an intuitive thermodynamic abstraction defining the planetary-scale chemical composition at reference levels of temperature and pressure. For example, if we burn a sheet of paper in such a world, and the ash and gaseous products further decay, then all the information concerning the chemical composition of the paper will eventually be degraded into quantum thermal noise and irradiated into the universe as heat. Chemically-encoded information is diverse and considered to be everything that is not in a state of maximum entropy in the world. Such information might include the chemical composition of various materials, such as amino acids, sugars, organic membranes, and bones, and the chemical structure of a light-emitting diode, a fuel injector, and other entities. Occupants of the world can use such objects of chemically encoded information to store the highest-level functional information. Thus, we should consider quantum information to be absolute, information in a chemical configuration is relative to its world, and functional information is relative to those to whom it is readable (Jablonka 2002). For example, imagine that one delivers a written paper document to a highly evolved species in an alien Earth-like world. Those aliens would not be able to read the functional information in the writing on the document, but would be able to decipher the molecular structure of the paper.

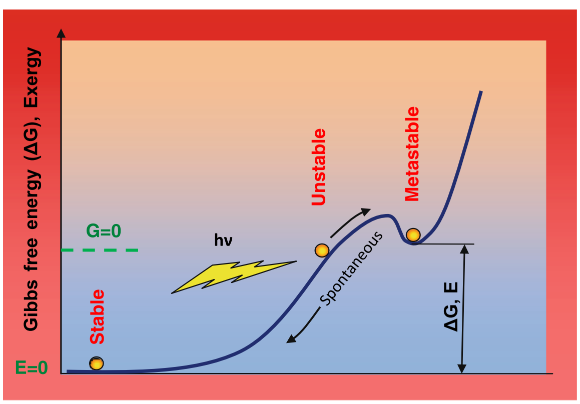


**Fig. 1** The metastable state as a perishable chemical information repository. The metastable state of elevated potential energy remains that way, at least for a while, and requires some perturbation for the return to a low, stable state. An external energy push is needed for potential energy to return to an elevated metastable state. In the case of ordinary matter, information can only be 'written' in a sequence of quantum energy jolts, pushing matter into reconfigured metastable states. The matter of ordinary atoms is an elementary medium in which chemically-encoded information can be stored in metastable bonds. Gibbs free energy, *G*, is the chemical potential with primary usefulness in recognising the chemical (meta)stability points and the spontaneous flow of the chemical reactions. The standard Gibbs potential is defined for a standardised state of chemical elements, which is typically well above the lowest energy state when such elements react in an environmental mixture. Exergy, *E*, essentially defined as the Gibbs potential ($\Delta E = \Delta G$), has the advantage of having its state of $E = 0$ defined precisely at equilibrium with the environment. Matter free of any chemically encoded information at a given temperature is in a state of maximum entropy. The lowest potential energy state is stable and in total equilibrium with the environment. Therefore, 'writing' is the delivery of energy in a manner such that after the writing is completed, the metastable chemicals of the writing are identified, and local entropy decreases as a consequence of the configuration of chemical ordering. The exergy of a system represents its chemical (physical) information state

### *Origin and loss of chemical information*

If an imaginary world without an energy source remained untouched at constant temperature *T*, eventually all of the local disequilibrium would disappear and all metastable states would empty, reflecting spontaneous thermal decay. This world would reach a state of maximum entropy, i.e., Boltzmann's 'heat death'. Here, we consider a thought experiment using such a 'dead' world with a composition capable of covalent and ionic chemical bonding. Before the ultraviolet band (UV) pulse irradiates the imaginary world, there is uncertainty concerning which molecules would form and remain preserved. This uncertainty represents the missing information prior to the experiment. After the UV pulse irradiates the planet, the remaining photochemically synthesised metastable molecules (Ranjan and Sasselov 2016) remove this uncertainty by holding experimental outcome information. These newly synthesised, metastable molecules decay unevenly, depending on the molecular structure and local environmental conditions. These molecular decay times vary vastly among different molecules. For example, metastable organics might have aqueous solution half-lives that range from minutes to billions of years (Lazcano and Miller 1996). If these molecules were left to decay indefinitely, then the imaginary planet would slowly return to its original 'heat death' state. Should the UV source be reignited prior to the return of the planet to the dead state, more complicated molecules would form based on those preserved from the previous experiment. This chemical information build-up, without intent or purpose, reflects natural experimentation, where natural selection facilitates the reuse of molecules that survive environmental stress.

Thermal molecular jiggling (spontaneous erase), photon absorption (photolysis), or bindings with other molecules can erase the information in a metastable chemical (Fig. 1). This latter process is common in metabolic reactions where the partial loss of previously stored chemical energy occurs. In all of these cases, chemical (or physical) potential energy dissipates into low-level thermal quantum information, which eventually diffuses out of the world and into the colder universe as heat through an increase in entropy. The irradiation of the quantum 'ash' of the 'dead' information into the universe makes such information irrecoverably lost to the world.

Chemical information storage is proportional to the temperature of the local environment. A substantial increase in temperature would result in the massive decomposition of stored information. Increasing the temperature of our fictional paper message would induce decomposition. This is true for all biological, organic material and any other material used in industrial manufacturing processes. In contrast, decreased temperature increases the survivability of chemical and functional information and enables the storage of more functional information in the same chemicals.

### *Origin and loss of functional information*

In his brilliant analysis of Maxwell's demon, L. Szilárd (Szilárd 1929) proposed that the possession of functional information might have thermodynamic consequences. It was shown by (Brillouin 1953; Bennett 1982) and (Toyabe et al. 2010) that chemically (or physically) storing functional information bit value requires at least $k_B T \ln(2)$ of thermodynamic work, where $k_B$ is Boltzmann's constant and $T$ is the environmental temperature. This thermodynamic work represents the energy needed to instil information into matter (Fig. 1). Thus, it takes a jolt of energy of at least $k_B T \ln(2)$ to store one functional bit of information chemically or physically into a metastable state, where 'physically' refers to information storage by means of metastable physical mechanisms such as those in electronic computers.

Functional information written over a chemical information base has been recognised in information theories, texts, digital computers, genomes, and other arenas. Functional information emerges as a result of a noisy search on the level of chemical evolution, as will be explained in the section of this study dealing with the emergence of functionality. When functional information emerges, it can be refined by higher-level experimentation such as conducted by sentient beings or on the level of biological functional information by Darwinian evolution. The erasure or 'death' of such functional information, the cornerstone of Darwinian natural selection, is viewed in terms of the Landauer principle (Landauer 1961; Bérut et al. 2012), where any loss of functional information results in the conversion of some free energy into heat and in a corresponding increase in thermodynamic entropy.

Because any functional message can be written in more bits than the minimum necessary, a functional bit of information can be chemically encoded in multiples of $k_B T \ln(2)$ to achieve better message survivability and reading resolution. In the metaphorical message on paper, increasing chemical information bits would mean the use of thicker, more rugged paper and thicker writing ink. When considering the messaging efficiency, multiples of $k_B T \ln(2)$, required for encoding functional information, are as close as possible to a value of one. Example of such tightly optimised functional encodings include digital data communication devices.

The thermodynamic-entropy-like mathematical tool called Shannon entropy (Shannon 1948) should not be confused with thermodynamic entropy, which reflects the chemical or physical configuration at one level lower. Indeed, the relation between the two entropies becomes less clear in a limiting case, where an information bit of encoded functional information approaches the $k_B T \ln(2)$ limit. The two entropies probably converge in such a limiting case.

For instance, the *Escherichia coli* (*E. coli*) bacteria is thought to contain 0.6 MB of specific genetic functional information (Blattner et al. 1997), while the entire *E. coli* bacterium contains up to 20 GB of discoverable chemical information calculated after (Morowitz 1955). Both forms of information are readable to us. Genetic information can be measured in terms of Shannon entropy, and this information represents white paper written instructions for the functioning of *E. coli*.

As the information of quantum systems is not originated and cannot be destroyed, the natural selection mechanisms must be classical. **The proposition of information 'death' is essential for natural experimentation and fitness selection.** The chemically metastable exergy stored in the world can be viewed as an experimental information repository available to nature.

### *Exergy as chemical information potential*

Engineers, and recently economists (Warr and Ayres 2012), have recognised the advantageous treatment of energy conversion into thermodynamic work through exergy. Chemical exergy, introduced by (Rant 1956), is defined as the maximum work obtained when the considered system is brought into a stable reaction with reference substances present in the environment at its reference pressure and temperature. The beauty of using exergy theory lies in the fact that the chemically stored exergy in the world also represents stored chemical information potential (Fig. 1). If we return to the thought experiment with the imaginary world irradiated with UV light, we can conclude that photochemically-generated metastable molecules represent increases in free energy, exergy, and chemical information. All these notions are equivalent. As UV light can be converted into thermodynamic work, this energy can also be considered as an exergy source. The UV light of the stars in the universe carries low-thermodynamic-entropy quantum information to worlds, where this information is partially converted into stored chemical information or chemical exergy. Thus, stars are exergy sources for feeding chemical exergy to worlds (Chen 2005).

## Pillar 2: Exploration mechanisms

### *A noisy search through cybernetic exploration and exploitation*

In biological theory, functional information is sometimes regarded in terms of noisy information channels, where certain specific, genetic information is communicated relative to processes in the organism (Yockey 2005). Newer approaches, however, depart from this view, as genetic information is somewhat less specific than originally thought (Longo et al. 2012). The exploration 'decision' processes at an intracellular level depend on noise for input (Balazsi et al. 2011). (Tyagi 2010) elegantly explained this notion using *E. coli*. Assuming that genetic information is specific, the test bacteria under the same conditions should be configured in the same way. However, this did not occur in his experiment, and the tested *E. coli* assumed varying, noisy, configurations.

In our earlier thought experiment on the UV-illuminated world, we skipped the factual exploratory 'choices' of nature. Experiences in the field of AI (Koza et al. 1999; Traulsena et al. 2009) and biological evolution (Balazsi et al. 2011; Tyagi 2010) have shown us that the initial exploration and exploration beyond the known range requires distortion or mutation of the information. A noisy search is conducted in nature with chemical and functional information. This noise makes biological information less specific and thus ensures the necessary variation. Noise sources comprise thermal molecular jiggling, radiation noise for chemical experimentation, or visual and audible noise (Mehta et al. 2012) input that sentient beings receive, or any other form of natural noise capable of influencing an evolutionary search.

Exploration and exploitation are two distinct search mechanisms in evolutionary optimisation algorithms. Now, do not let the word 'algorithm' sway you into thinking that these processes are somehow isolated to something done with computers. Quite the opposite. These mechanisms were first identified by evolutionary biologists soon after the genetic mechanisms of evolution were discovered. Even before these mechanisms morphed into digital computers in the 1990s, from the 1950s to 1980s economists increasingly realised that technological development resembles that of biological evolution and the terms "exploration and exploitation" were first proposed in the economics of innovation in technology (March 1991).

Let us return to the 1950s. Geneticists realised that information contained in genes was now and then modified by mutations which caused the appearance of new modifications of life. Usually, a new variation of simple life has a low chance of survival and the chance that this new entity has a fitness improvement over the previously known inventions of nature is very small indeed. Mutations generate changes that can reach any combination from the combinatorial space. This makes the probability that a mutation search point ends up near an existing solution remote. Therefore, a mutation-based exploratory search is also referred to as a far search. This far search does not need any previous knowledge. Exploration thus boldly goes into the unknown. If the new solution has at least sufficient fitness, its information will remain preserved. If not, it will be deleted.

It took until the 1993 work of Hilario and Gogarten (Hilario and Gogarten 1993) before the horizontal gene transfer of complex life became understood. Genetic information crossover in sexual reproduction was of course known beforehand, but was poorly understood. Its function in protecting the genetic material was quickly recognised; **its function in the execution of an exploitation evolutionary search** became clearer after Hilario and Gogarten's work was combined with the experiences of the in-silico computational experimentation with evolutionary search algorithms that became widespread in the 1990s. Nature invented numerous ways to exchange these complete segments of prior knowledge. The best known is sexual reproduction, where the genetic material of relatives is transferred. In this way, the offspring would have a high chance of survival and changes to the phenotype would be small, incremental, and seemingly continuous. This is an exploitation near search. Exploitation is capable of a limited far search as horizontal gene transfer can be achieved in nonsexual ways that overcome the safeguards of sexuality, but these events are rare. Nevertheless, even this exploitation far search is limited to the knowledge range previously identified by exploration. It cannot extend beyond it.

**Why is an exploitation search so much more advantageous than an exploratory far search?** A mutation search might yield an improved solution in one in a million, for example. An exploitation search through information crossover might yield an improvement in just one in ten trials (Doerr et al. 2008). And nearly all subjects survive. The advantage increase might not be as radical as would be achieved in a far search, but to beat competitors it is sufficient if you are 5% more fit. There is no need to be 300% more fit to win the local struggle for evolutionary fitness.

And indeed, genetic mutation rates in biological evolution first decreased when evolution moved from RNA to DNA and later again when sexual crossover was introduced (Drake et al. 1998). Changes to mutation rates were several orders of magnitude per transition. This inevitably means that exploratory far searches were pushed aside and replaced by more productive near searches (Szabó et al. 2002), which gave the fundamentally discontinuous biological evolution an appearance of gradual change.

**What about cognition, technology, and AI?** All of them have been identified as employing exploration and exploitation principles when dealing with information and optimisation/adaptation. Human inventive thinking (Campbell 1960) had been associated with an evolution-like process even before C. Darwin published his famous book on evolution. As early as 1855, A. Bain (Bain 1855) discussed trial-and-error thinking as part of the human intellect. Cognition in humans obeys the principles described above. When a child is born, it possesses little prior knowledge. A newborn child starts a noisy search. He or she makes random-like experimental movements, which the child evaluates and thus slowly builds knowledge in his or her neural network. Later in life, we also store highly abstract knowledge that originates in experimentation. Prior knowledge is again used thorough exploitation. More on the cybernetics of cognitive thought experimentation can be found in (Donoso et al. 2014).

**I have saved examples regarding AI for last** Such use is usually referred to as evolutionary computation, or even better, evolutionary algorithms (EA) (Črepinšek et al. 2013). New inventions in technology can be identified in this way (Koza et al. 1999). In general, EA is used in various applications where a previously unknown solution to a problem must be located within a predefined exploration space. Nowadays, the use of EA is moving to various network optimisation jobs and most notably to the intelligence behind self-driving cars, where they must mimic the driver's improvisation and decision-making capacity.

### *Increased complexity through the information addition and the emergence of functionality*

The increasing complexity of competing elements increases experimental complexity (Gutowski 2005). Competitors must add similar properties, thereby also increasing complexity. Once a high level of complexity is attained, complexity adaptation must be considered; a decrease in complexity may become advantageous. For example, jet engine complexity decreased over the years to improve efficiency and reliability (Koff 2004). Polymerisation is a mechanism of chemical information addition (Andrieux and Gaspard 2008) and experimental complexity build-up (Joyce 2002; Walker et al. 2012) in chemical evolution. In the case of evolutionary algorithms in the field of AI, numerical genome elongations serve as a mechanism for increased member complexity (Decraene et al. 2011).

The authors of in silico noisy search experiments (Walker et al. 2012) have demonstrated the emergence of functionality through such information addition. In general, functionality emerges as a consequence of a noisy search where unfit (those with short decomposition times) polymerisation attempts perish and selected configurations with functions that aid survivability, such as resistance to UV radiation or resistance to thermal or hydrolytic decomposition, remain. Such informational polymers are expected to have configurations that are non-random and can thus be associated with a configurational component that is recognised as biological functional information, as explained by (Yockey 2005) in Chapter 6.

These information addition processes take advantage of horizontal information exchange, which when genes become available is considered to be horizontal gene transfer (Hilario and Gogarten 1993; Woese 2002; Arnoldt et al. 2015). There is the limitation that added and exchanged information, likely resulting from the pool of prior exploration or pre-assembled composite information, must exist beforehand.

In the case of human inventions, 'outside-the-box thinking' is associated with the addition of a noisy search component. Adding a pre-existing component from a remote technical field still involves an inventive step (Moir 2012), whereas adding a known component from the same field of arts is not considered inventive but, rather, a form of non-inventive horizontal information exchange in technology.

### *The Miller-Urey experiment revisited*

The Miller-Urey (Miller and Urey 1959) (MU) experiment showed that amino acids can form from certain plausible early Earth prebiotic components and a sparking exergy source. However, the greater importance of the MU experiment might lie elsewhere. The MU experiment generated a small-scale natural experimentation model involving both exploration search and chemical information addition through polymerisation. Chemical information addition generated high-molecular-weight tholins at the bottom of the experimental flask. These tholins represent the point of experimental exhaustion. Prolonged experimentation did not influence the outcome, as heavy molecules excluded themselves from further experiments by accumulating away from the exergy source. In this case, reduced diffusion of chemical information through over-polymerisation exhausted the experimentation process. Unrestricted polymerisation is a problem requiring further consideration, as overcoming this obstacle on early Earth might have been a decisive pathway for further chemical evolution into individual entities rather than a giant polymerised rubbery blob, which could have formed instead. For evolution to produce several cooperating or competing agents, there must be a naturally present condition that limits polymer overgrowth (Walker et al. 2012). The MU experiment showed another profound property of nature: **nature can conduct inventive experimentation, a form of natural selection, without heredity and/or self-replication**. Experiments are conducted in parallel with the direct production of experimental chemicals without the need to replicate these materials from a template. In the MU experiment, a sparking source induced gaseous components to excite, ionise, and subsequently decay. Excited and ionised components primarily relaxed and recombined, but while in an excited state, some components bond to other neighbouring molecules. The end-results only showed chemical products with decay times long enough to survive until a human observer evaluated them.

An experiment to test for the presence of bioinformation (i.e., functional information) in tholins can be devised. An MU-like experiment could be devised to prevent the deposition of the resulting tholins, and by varying the molecular selection pressures (hydrolysis, thermolysis, photolysis) the structural correlations of the resulting tholins to applied pressures should become apparent.

## Invention processes

### The generalised invention process

Consider an invention process that comprises an external exergy source and an experimental space with configurable particles, which can receive work to reconfigure their free energy state. The invention process in the experimental space consists of the experimental set-up and the experimentation. The experimentation involves the exposure of information to the selection process. This selection process represents natural selection, where entropy-generating processes selectively erase stored information.

### Primary process – the primary exergy efficiency of chemical information generation

The primary process is the equivalent of an initial information injection into an optimisation machine. It is a 'far from equilibrium' process, where an exergy source fills metastable chemical states. Examples of such processes are the photochemical formation of organics, biomass formation, and the injection of initial random numbers into an evolutionary computation machine. Primary exergy efficiency is introduced. Primary exergy efficiency is a ratio between the exergy stored in metastable chemical/physical structures and the exergy delivered into a system.

The time derivatives will use the following notation: $X' = dX/dt$. In a generalised experimental set-up, the quantum of source exergy $\Delta E$ is delivered into the experimental space and converted into thermodynamic work $\Delta W$. This work packet $\Delta W$ might push the system into an elevated metastable state $\Delta G$. In a special case of infinitely slow delivery, a reversible change of $\Delta G = \Delta W = \Delta E$ is possible (Jarzynski 1997; Toyabe et al. 2010; An et al. 2014). A microscopic exergy efficiency $e$ for a realistic, finite time process should be introduced: $\Delta G = e\Delta E$. The primary exergy efficiency $e$ shall be within the interval of zero to unity. Zero represents zero or negative changes in the free energy, and unity represents positive and thermodynamically reversible energy storage. The chemical information potential, $B$, is introduced here. The positive stored energy $\Delta G$ results in a corresponding stored information potential $\Delta B_{gen(erated)}$ (Eq. 1) in bits of information:

$$\Delta B_{gen} = e\Delta E/k_B T \ln(2) \tag{1}$$

This information potential packet is added to a larger macroscopic experimental set-up preocess (Eq. 2), where $E'$ is exergy flow into the system in watts and $B'_{gen}$ is the flow of stored information potential in bits/s:

$$B'_{gen} = \varepsilon E^{'}/k_{\mathrm{B}} T \ln(2) \tag{2}$$

The physically stored information potential, $B'_{gen}$, enters the experiment, where entropy-generating, destructive processes erase information at rate $B'_{eras(ed)}$. $B'$ is the net information potential accumulation rate. The net information potential accumulation rate, $B'$ (Eq. 3):

$$B^{'} = B'_{gen} - B'_{eras} \tag{3}$$

The closed thermodynamic system experiences $B' \leq 0$, reflecting the 2nd law of thermodynamics. However, an open system might experience periods of $B' > 0$ through exergy inflow and corresponding macroscopic exergy efficiency $\varepsilon = \langle e \rangle$, where $\langle\rangle$ denotes the average over the ensemble.

There is an experimental space with the innovation process running when invention process and experimental information diffusion occur. Experimental information diffusion is the ability of a system to exchange the surviving information potential $B$ among experiments.

### The functional information innovation process

Functional innovation in natural Darwinian experimentation and technological developments through human invention operates on the 'paper surface' generated by the underlying chemical information. Functional innovation is thus limited by the world's chemical information generation. **On the large scale, the functional development of a world can be measured through the generation of chemical information and its exergy efficiency. The efficiency indicates the quality or developmental stage of the functional information.** The direct quantitative description of worldwide functional information-generating innovation is impossible, reflecting the complexity and chaotic nature of experimentation, but efficiency measurements might be an elegant method for obtaining insight into the developmental stage of natural experimentation.

### *Subspaces and exhaustion*

The abstract division of an experimental space into subspaces with different efficiencies and productivities is a matter of convenience. Civilisation might have the static experimental fields (sub-spaces) of metallurgy, agronomy, mining, robotics, and others. Experimental (sub-)spaces in nature might also be dynamic, where the experimental environment changes over time. All experimental spaces and sub-spaces are finite with finite maximum configurable or discoverable (when previously configured) information. Thus, experimentation can reach an exhaustive point at which the results diminish to small refinements. If the experimental space is at least quasi-static, the experimental process would eventually uncover the entire experimental space and store information concerning accessible yet unrefined inventions. Exhaustion can be viewed simply as a convergence of the optimisation algorithm. The closer to the optimum the solution is, the slower the convergence of the evolutionary search will be.

## Biological innovation and exobiology

There has been much success since 1800 in the identification of the physical pathways that played a role during the evolution of the Earth (Yockey 2005). The experiments of (Miller and Urey 1959), for example, demonstrated how short polymerised organics could form from a sparking exergy source. Other exergy sources include geothermal activity (Miller and Urey 1959), various radiations (Miller and Urey 1959; Chyba and Sagan 1992), hypersonic entry shocks (Chyba and Sagan 1992), or any other forms of exergy that do not originate from previously stored exergy. Chemically stored exergy should be viewed as stored information from prior experimentation. The exergy flow from photon radiation is typically assumed to be the dominant source of chemical productivity (Chyba and Sagan 1992). Other exergy contributions such as geothermal, atmospheric electric discharge (Miller and Urey 1959; Chyba and Sagan 1992), and background ionising radiation are typically small (Miller and Urey 1959; Chyba and Sagan 1992). In addition, one cannot neglect the potential information exchange between celestial structures within a cosmic system through various impact ejections (Gladman et al. 2005) and dust particles (Chyba and Sagan 1992). Dynamic changes to the experimental space reflecting intermittent cosmic events, stellar radiation variations (Chyba and Sagan 1992), and the influence of life itself might result in the loss of information. Any small amount of preserved information finds the changed environment as a beneficial new experimental space that adds new potential solutions to the preserved solutions.

### *Natural experimentation sub-spaces on other worlds and the Earth's silicate melt sub-space*

The atmosphere of Saturn's moon Titan, for example, has two distinct, experimental spaces separated by two different UV bands (Tamburelli et al. 2014), where intense natural experimentation can be expected. In contrast, celestial bodies with liquid water under an ice crust, e.g. Europa and Enceladus, are places where only moderate experimentation is expected to have occurred, reflecting the low geothermal exergy availability (Chyba and Sagan 1992). If mere geothermal disequilibrium under a solid crust were sufficient, then we would have observed signs of evolved natural experimentation beneath the Earth's crust. There, observed from the standpoint of chemical evolution, polymerised glassy volcanic minerals, such as obsidian, are the most evolved metastable structures (Zotov 2003). Silicate melts convecting under the Earth's crust at varying pressures receive geothermal exergy to decrease configurational entropy through polymerisation (Lee et al. 2003; Lee et al. 2004). At elevated temperatures, high kinetic energy enables the exploration of states of higher potential energy. At sufficiently high pressure, and even at somewhat lower temperatures, the shape of potential wells changes in a way that gives rise to new configurations (Mysen and Richet 2005), derived from horizontal chemical information exchange in silicate melts where large oxide structures diffuse and exchange their locations within the polymerised silicate matrix (Wang et al. 2014). The region of polymerising silicate melts can be viewed as Earth's separate genesis in the prebiotic, chemical evolution stage.

Saturn's moon Titan does have a patchy liquid surface and a sufficient solar exergy flux (McKay 2014). It has two atmospheric, liquid, and possibly other networked experimental spaces. The identification of any build-up of substantial accumulated experimental information in our solar system (other than on the Earth) is likely going to occur on Titan. C. McKay and H. Smith (McKay and Smith 2005) proposed how metabolic processes on Titan could be detected through atmospheric composition. Subsequently, Cassini/Huygens provided evidence, but not conclusive evidence, of the $H_2$ vanishing towards the ground (Strobel 2010; Niemann et al. 2010). Nevertheless, these findings are as close as we have come to understanding Earth-independent genesis of life.

## Microscopic productivity limits

The chemical information experimental set-up is a micro-process where the laws of statistical mechanics come into play. The actual conversion processes require time to complete. (Jarzynski 1997) and (Crooks 1999) explained that only infinitely slow conversion can be thermodynamically reversible. The economy of life, however, dictates that these processes should be fast in order to prevent entropy-increasing processes from damaging the stored information. Conversion becomes less efficient with the increasing speed of the process. Thus, productivity involves fundamental inefficiency. The higher the productivity, the more exergy is required for the same amount of information modification and storage, hence decreasing the efficiency. Higher productivity increases exergy consumption (England 2013). This limitation concerns biological entities, electronic computation, and manufacturing processes. A person who runs will notice that doubling one's speed does not simply double the 'effort'. The same happens whenever doubling the speed of an industrial robot or overclocking a microprocessor to double frequency. Increasing productivity without fundamentally improving the apparatus disproportionately increases exergy consumption. This property might seem worrisome as economic growth most often occurs through productivity gains, depending on increasingly more difficult fundamental improvements to the apparatus through innovation. (England 2013) indirectly showed that invention prefers the replication of an apparatus with a shorter lifespan produced at a higher rate, consistent with observations in technological development (Prakash et al. 2016).

### The invention of metabolism and fossil exergy efficiency

As is the case with all inventions derived when an opportunity presents itself, the moment sufficient stored information potential $B$ is accumulated, an opportunity to consume the stored information becomes apparent. Because $B$ is also accumulated exergy, $E_{accumulated} = B\, k_{\mathrm{B}}T\ln(2)$, it is possible to invent a heterotrophic process (Stoker et al. 1990) that benefits from 'metabolising' stored $B$. Subsequently, the basic equation for the experimental set-up and information generation $B'_{gen}$ Eq. 2 becomes Eq. 4, and Eq. 3 for $B'$ becomes Eq. 5:

$$B'_{gen} = \varepsilon E'/k_B T\ln(2) + \varepsilon_F B'_{con(suming)} \tag{4}$$

$$B' = B'_{gen} - B'_{eras} - B'_{con} \tag{5}$$

where $B'$ is the information accumulation rate and $B'_{con}$ is the rate of consumption of pre-existing chemical information, such as biomass by collective organisms and fossil fuel by a society. $B'_{eras}$ is the information erase rate, which in biological systems represents a loss of information, reflecting corrosive and imperfectly efficient metabolic processes. Eqs. 4 and 5 are now general qualitative equations of natural experimentation, representing biomass generation analogous to the world's gross domestic product, and the two efficiencies, $\varepsilon_F$ and $\varepsilon$, describe the rough quality of the information. Note that eqs. 4 and 5 do not separate chemical and functional information.

Metabolic life burns stored information for purposes beyond invention and replication. A new 'fossil' efficiency, $\varepsilon_F$, for burning or metabolising stored information $B$ has been introduced. Biological metabolism and the use of fossil fuels are evolutionarily equivalent innovations. They are both opportunistic uses of 'free' exergy 'lying around' and previously stored in the primary process.

#### *Earth exergy efficiencies*

The economic development of modern civilisation experienced step-wise discoveries of new experimental fields. These discoveries increased gross domestic product (GDP) through the broad use of direct exergy $E'$, available fossil exergy $B$, and increases in efficiencies. Currently, the Earth's biosphere successfully converts incident solar exergy radiation of 119,600 TW to 2.9 TW (Chen 2005) of stored chemical exergy $\varepsilon E'$, with an approximate primary efficiency $\varepsilon$ of 0.00003. Economic growth requires a constant increase in the information generation rate $B'_{gen}$, which we could consider to be a proxy of GDP. (Ayres et al. 2003) showed that much of this growth reflects improvements in fossil exergy efficiency $\varepsilon_F$ and the subsequent rebound (the Khazzoom–Brookes postulate) effect to broaden fossil exergy use. These data (Laitner 2013) and the data from previous studies (Ayres et al. 2003) demonstrated that U.S. fossil exergy efficiency increased almost linearly from 0.025 in 1900 to 0.139 in 2010 (Ayres and Warr did not strictly consider exergy efficiency as in Eq. 4). The two efficiencies are for the time the only measures of the quality of the accumulated functional information.

Fossil exergy efficiency, $\varepsilon_F$, represents the efficiency of the utilisation of previously stored chemical exergy. This metabolic-like process exists on the shoulders of the primary process, which stores this chemical exergy with primary efficiency $\varepsilon$. **This relation holds for the whole biosphere encompassing both the living and the technological. In the context of this essay, any consumption of exergy is considered experimentation.** Biological and industrial replications create experiments where information is either gained, lost, preserved, or combined into a new experiment where more exergy is consumed.

## Economics and innovation slowdown

As can be expected, technological evolution relies on far and near searches. Until 1900, searches were predominantly exploratory far searches, as discovery-level inventions were accumulated. Examples of discovery-level inventions include fire, electric power, wire and wireless messaging, fossil fuel power, pharmaceuticals, and many others. By approximately the year 1900, enough of these far-search points had been accumulated that it became clear that the refinement thereof through systematic research could be more advantageous. Surely it was evident that improvements to the automobile made more sense than exploring for an entirely alternate mode of transportation. Improvement of existing ideas seems to be the way to go. This is how exploitation slowly replaced exploration in technology.

**We, humans, evaluate technological inventions through our own evolutionary fitness.** An invention whose utilisation cannot enhance the user's fitness will be rejected and deleted from use. This is how biological natural selection finds its way into technology.

**"Endogenous growth"** is an idea in economics that claims that the best growth results can be achieved through investment into targeted R&D. The downside of this paradigm is that it calls for a reduction in far-search exploration, which happened, as evidenced in Youn's analysis of patents (Youn et al. 2015). A far search is deemed too risky and uneconomical. No one seems to have noticed that such overuse of exploitation necessarily results in ever smaller improvements in consecutive inventions.

### Innovation exhaustion and economic slowdown

(Gordon 2012) and (Buchanan 2015) documented general innovation contraction in the U.S. Specifically, for silicon chip technology (Esmaeilzadehy et al. 2011; Austin 2015) it is still technologically possible to further decrease microprocessor resolution, nevertheless, the efficiency boundaries in multiprocessor die arrangements have been reached and the cost jumps resulting from the introduction of even smaller chip resolutions yield a positive return with ever more difficulty (Austin 2015). Even if the number of transistors on a chip is doubled, such efforts will no longer result in equivalent performance gains (Austin 2015). A similar situation can be observed with conventional drugs. Previous studies (Scannell et al. 2012) reported an increase in efforts towards pharmaceutical discovery in accordance with 'Eroom's law' (Moore's law in reverse). These observations were correct, but the analysis seems to be wrong. However, these authors did notice a 'low-hanging fruit' problem, suggesting that easy things have already been discovered. Nevertheless, the authors ascribe the innovation slowdown to other factors. This and other slowdowns in nearly all engineering fields reflect 'the low-hanging fruit' problem or, more precisely, the problem of the exhaustion of the experimental space. The most obvious example is the near exhaustion of thermodynamic-conversion efficiency improvements in combustion engines in the late 1960s (Ayres et al. 2003).

Since 2010, D. Strumsky, J. Lobo (Strumsky and Lobo 2015) and others have reported that there is an ever-increasing portion of patents representing refinements or combinations (crossovers) of previous ideas. Strumsky et al. (Fig. 2) propose the number of technology codes

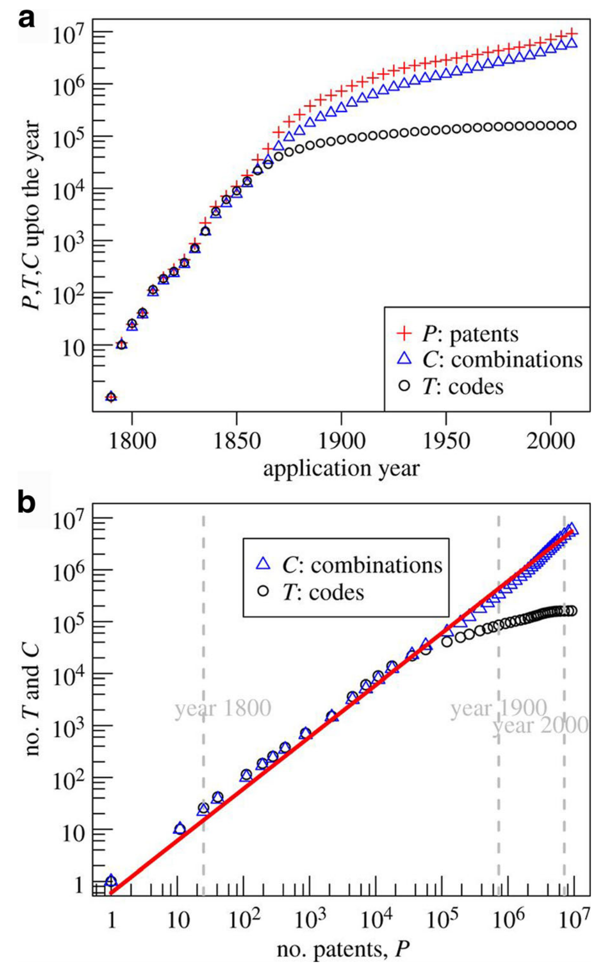


**Fig. 2** The number of patents, combinations of technology codes and technology codes as inventions accumulate in the system. (**a**) Shows the increase in these quantities over time. (**b**) Shows their increase as functions of the number of patents. The red solid line is a linear fit with combinations C. The grey dashes in (**b**) mark the number of patents for the years shown. Because the number of patents increases approximately exponentially in time, the gaps between year marks get shorter and shorter as one moves to the right of panel (**b**). Reprinted from (Youn et al. 2015) under the Creative Commons license

(areas of prior art) as an indicator of inventions incorporating new exploration fields and use this indicator to present convincing evidence that inventions identifying new experimental fields are indeed lagging. This evidence highlights the exhaustion of individual technical fields.

### How modern communication technology contributes to the slowdown of economic growth

Economic growth in GDP per capita can only be due to increased energy intensity (capital investment in more of the same) or through genuine innovative efficiency improvements in technology (efficiency improvement to the apparatus). Since the year 2000, there has been token productivity gain in the OECD member states (Baldi and Harms 2015).

It can be observed in Fig. 3 that most of the historical technological development of human inventiveness has remained constrained. From all of the above, we can presume that the low level of observable growth up until 100 years ago was due to small improvements in information storage (writing, printing) and information communication enhancements. For exploratory inventions, information handling is irrelevant, but for exploitation inventions (combinations) communication is essential. There can be no combinations if original exploratory 'search successes' remain undiffused.

Figure 4 illustrates important communication upgrade of society in the last 100 years (Ellis et al. 2016). The presented speedup corresponds to the dramatic increase in the innovation rate (Fig. 3) in the last 100 years. This can be taken as evidence by simultaneously observing Youn's analysis of patents (Fig. 2), where it is shown that the inventions of the last 100 years are predominantly of a combinatorial nature. From this a stark conjecture follows: progress in communications technologies greatly accelerated exploitation searches in society's technological adaptation leading to the speedy exhaustion of the exploration space identified in explorations carried out before the onset of the twentieth century.

There can be no hope for AI-driven technological singularity. Any further enhancements in combinatorial capacity, which is what AI does, would merely accelerate convergence and exhaustion.

## Conclusions

Naturally occurring metastable chemical and physical states can serve as testable information carriers. In the presence of a substantial thermodynamic disequilibrium, information is constantly generated and tested, representing a new view of chemical reaction models where reactants are observed in terms of survivability. Pre-biotic chemical evolution does not require replication with explicit heredity but, rather only needs information addition, diffusion, and an exergy source. A form of informational 'heredity' in terms of an exploitation search is required, however.

The information potential, *B*, is introduced to aid in the understandability of chemical evolution informational processes. Because any functional information is superimposed over chemical information, it represents the maximum functional information in a world. The physics-based necessary condition for evolution can be defined as the requirement for an experimental space with the innovation process running. However, this is not a sufficient condition in itself. The sufficient condition is only fulfilled when innovation-generated information exceeds the amount of information lost to deleterious processes.

Evolutionary optimisations (i.e., inventive processes) have three recognisable phases. Initially, this is a random, noisy exploratory search. Once exploration yields sufficient stored information (i.e., knowledge) the evolutionary process transits to an exploitation search, which can be recognised by a lower number of information 'mutations' and increased combinatorial inventions. An exploitation

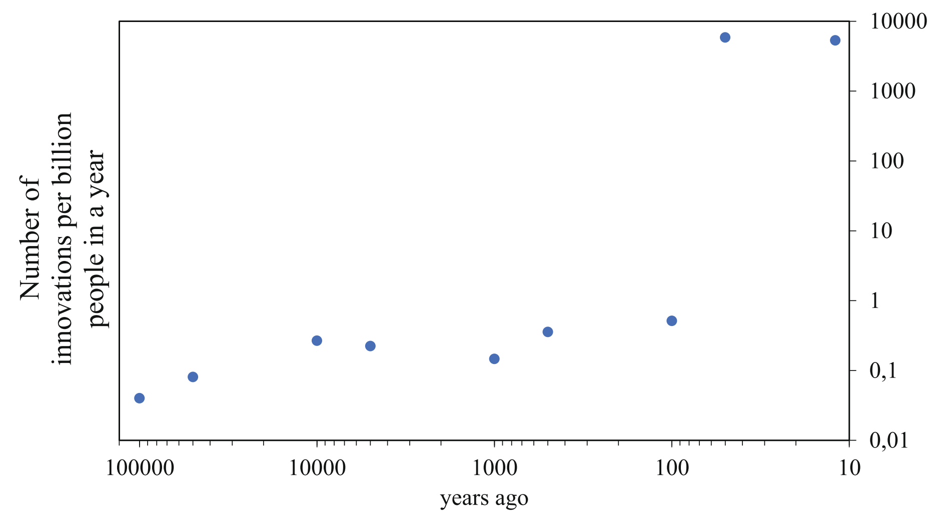


**Fig. 3** Historical inventiveness as the rate of innovations per billion people per year. Population data is from (Kremer 1993). The first seven data points from the left are counts from (Timeline of Historic Inventions 2017), while the last two data points are calculated from (Youn et al. 2015), assuming that 2% of patent applications actually see any real use. The 2% ratio is derived from 40,000 U.S. triadic patents (Triadic patent families 1984–2014 2017) and 1.76 million patent filings in the U.S. (Total number of patents in force worldwide tops 6 million 2008). Triadic patent families are patents granted in the U.S., the EU, and Japan. It is presumed that triadic patents represent the most realistic proxy for real-world innovations

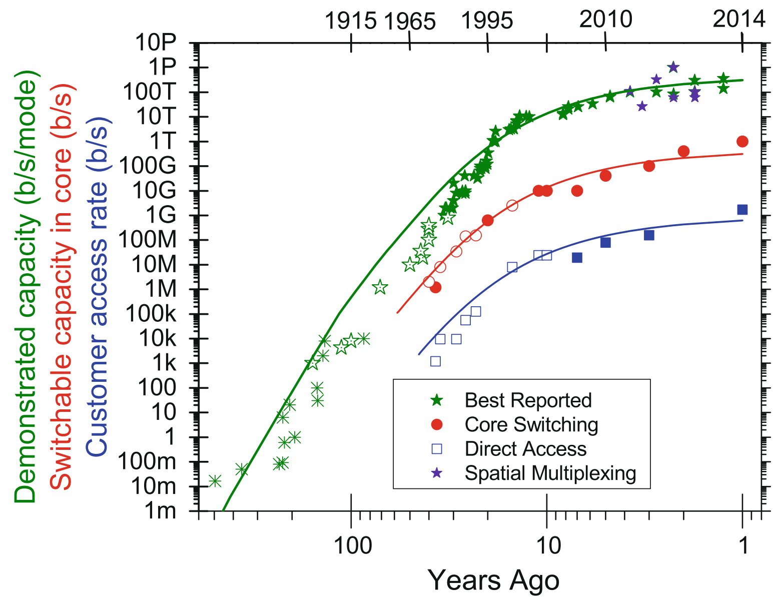


**Fig. 4** Evolution of communication capacity with time showing the best reported capacity including reports from scientific publications (*green*, *purple*), capacities switched within the core network from commercially available products (red) and data rates offered to residential customers in at least one country (*blue*). Symbols indicate use of free-space (crosses) or fibre (solid symbols) based optical systems or electronic systems (open symbols). Purple symbols represent spatial multiplexing. Reprinted from (Ellis et al. 2016) under the Creative Commons license

search greatly speeds up convergence towards optimal configurations. Improved communication between agents further speeds up convergence towards the inevitable exhaustion of the experimental space.

For economic development and technology, the statistical mechanics-based productivity limits suggest that the productivity of any process cannot be increased without a decrease in energy efficiency if no change is made to the apparatus. Changes to the apparatus in technology are becoming incrementally less significant due to exhaustion.

Human inventors also evaluate their own fitness gains through their inventions. If the societal (taxes) or organisational situation in a corporation, for example, is such that others would benefit from a tentative innovation more than the inventor, then he or she will strive to move elsewhere or to withhold worthy ideas.

Current innovative management strategies are oriented towards systematic approaches based on perceived needs, which frequently result in pursuing matters of already exhausted experimental spaces with ever-diminishing returns. The exhaustion of broader experimental fields can only be overcome through the identification of new broad fields via basic sciences being pushed into the risky unknown through exploration searches.

Exploration searches can be clearly distinguished from exploitation by not having definable, measurable goals. The measurability of the expected results should be taken as a strong indication that the prospective activity is exploitative rather than explorative.

Although our options as regards the metabolic uses of fossil fuels seem exhausted, Earth's primary exergy efficiency is merely 0.00003, which must be taken as indicating the direction of future exploration.

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The authors declare that they have no Competing interest.

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