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Research Article

Freedom and evolution in science

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ABSTRACT

This article is about evolutionary design and freedom and is based on my new book, *Freedom and Evolution: Hierarchy in Nature*, Society and Science [1]. There is a lot to say about this broad subject, therefore I've reduced it to the topics of thermodynamics, freedom and evolution, diversity and hierarchy, and science and freedom. First, I will present the terminology, which will be followed by the applications of the evolution of cooling technology for high-density heat-generating components in a packet. Finally, I will show why this book is important for you, the reader, as well as for the practitioner.

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1. INTRODUCTION

Evolution is the word for the changes that are occurring in a discernable direction in time. The changes and their direction are discernible to the observer. In fact, all of science comes from what the observer observes and discerns.

Freedom is the one word for all the physical features that endow the object or the system with the ability to change. No freedom means no change, no evolution, and no configuration (because configuration comes from an evolving design), and that means no direction of time, and no future (Fig. 1).

You may be surprised to know that freedom can be measured. We can measure it in terms of the number of degrees of freedom that the object has at its disposal. Freedom can also be measured in terms of the effect these degrees of freedom have on performance, efficiency, life, longevity, staying power (permanence), and benefit to the user. We get this idea even better if we question the meaning of evolutionary design:

Evolution:

Changes that occur in a discernible direction in time (process)

Freedom:

The physical features that allow changes.

Without them, there is no evolution, configuration, time, future.

Figure 1.

Figure 2 shows an icon of where we all come from and where we are going. Everything in nature is a moving system that morphs with freedom. This is an icon of the book of thermodynamics. The thermodynamic system in the blue domain is powered by energy coming from a source. This energy stream is converted partially into work or power, and the remainder is discharged *necessarily* to the ambient surroundings. In the blue domain I sketched many

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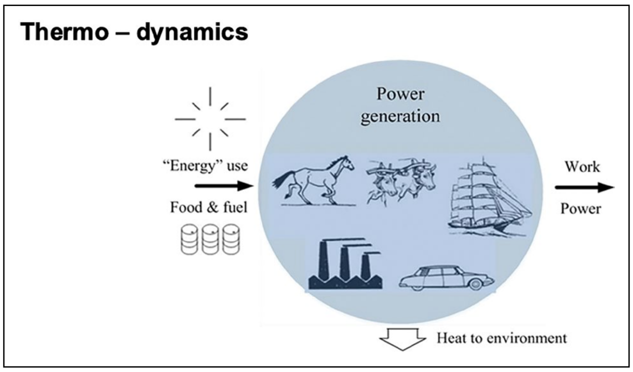
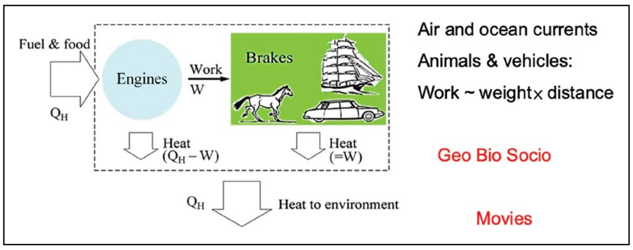


Figure 2.



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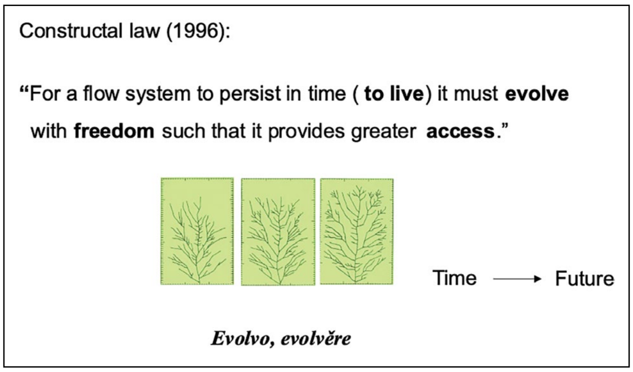


Figure 4.

configurations. Some are very old, and some are a lot newer. They suggest that the design that facilitates the conversion of the source energy (e.g., heating, fuel, food) into work has been evolving. So, that is evolutionary design, and it is only half the picture. The complete picture is shown in the rectangular box in Figure 3.

The drawings that in Figure 2 were in the blue domain are called 'engines' in Figure 3. In an engine energy goes in, heat comes out, and work comes out. The work is delivered to a moving system external to the engine. The point is that the work is dissipated instantly by moving something against its will. That is, against its environment. The movement dissipates the work completely into heat rejected to the ambient.

So, from a distance, if you look again at the rectangular box, heat goes in, and then the heat is rejected 100% from the rectangular box. In the meantime, however, movement has happened in the horizontal direction because of the presence of evolutionary designs in the blue domain and in the green domain. The designs are evolving so that the movement goes farther, becomes more efficient, and lasts longer.

To account for this new aspect of the thermodynamics that we all practice, I stated in 1996 the Constructal Law: "For a flow system to persist in time (this is the definition of "to live" in physics), it must evolve with freedom such that it provides greater access" (Fig. 4). This is the physics definition of life, because in thermodynamics we already have the physics definition of death. It is called the dead state, where the 'being' of the system (the state) is such that nothing moves. There are no changes at all. The boundaries show no deformations over time. So, the live state is the antonym (the opposite) of the dead state.

Important are the three words shown in bold letters in Figure 4: to **live** and to evolve with **freedom** for greater **access**. These words mean one and the same thing, which is **freedom** itself. Without the physical features that allow changes (called 'freedom'), there is no life and no meaning coming from the observed configuration. There is no movement, and no access.

Figure 4 shows a laboratory demonstration of the evolution in time of a river basin. From one time frame to the next, the architecture is changing. Yet it is always tree-like, or arborescent. There is also the direction in time, which can be shown with measurements. The direction is toward flowing more and more easily, meaning that the water on the horizontal area is being driven by progressively smaller peaks of altitude. The movie running from left to right is the time arrow called evolution, which is brought into thermodynamics by the statement of the Constructal Law.

By the way, evolution is a concept as old as science itself. It comes from the Latin verb *evolvo, evolvĕre*, which means to roll out or to roll forth. This word makes the mind imagine child birth. Everything that is comes from Mother Nature, a feminine entity, *Natura* in Latin. This is the mother word that has given birth to many other words in in the language of science that we speak today. For example, the words valve, vulva, and Volvo ('I roll'), the brand name of the Swedish automobile, all these words have the same origin as evolution.

With this law of physics, many researchers have shown that it is possible to predict not only the evolutionary designs that have been observed and documented, but also the future of designs. Figure 5 shows a large number of designs that endow all sorts of systems on Earth with locomotion (movement driven by power): swimmers, runners, and fliers. Widespread agreement exists between observed speeds of locomotion versus body sizes. The movers cover a wide range of sizes, from the housefly to the biggest ships. While airplanes appear to be deviating from the line of fliers, more recently, they've been brought in line with the animal fliers by considering the fact that the density of the medium in which

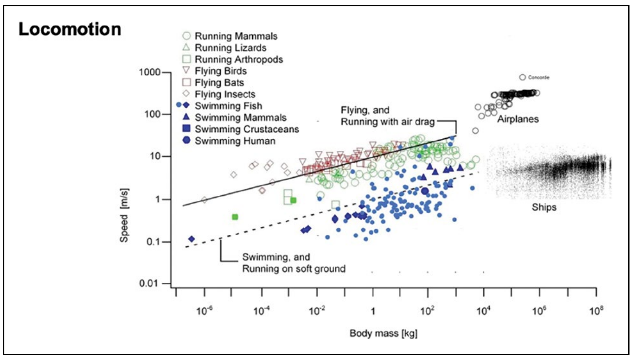


Figure 5.

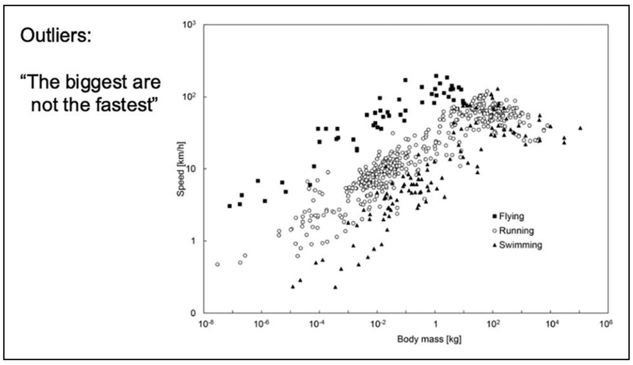


Figure 6.

the fastest airplanes travel is lower than the density of the atmosphere against which animal flight has evolved.

The agreement between the dots and the theoretical lines for fliers and swimmers is accompanied by a cloud-like distribution of data, the *diversity*. Figure 6 is a blowup of this region of the fastest movers versus body sizes. This is how the next idea comes to be. The cloud is about diversity and goes hand in hand with the predictable trend.

Figure 6 shows the extreme right side of Figure 5. In each of the three groups, whether fliers, runners, or swimmers, the fastest are not the biggest. The biggest animals are somewhat slower than their fastest relatives. The hump in the data has been used by many as an argument that the general trend is incorrect. The slogan for that point of view is that 'the biggest are not the fastest'.

In fact, the biggest turn out to be the fastest. The data shown in Figure 6 come from zoology and show the maximum speeds. Of course, the maximum speeds of animals have to do with the lifestyle of the animals. As such, the fastest animals, fliers, runners, and swimmers are the predators. The big animals that are fast are not the fastest; they are the grazers, the ones that move all the time and eat all the time. The average speed over the lifetime of a mover turns out to be in accord with the prediction that the trend is toward greater average speeds if the body size increases. This is clear in the evolution of airplanes: big commercial jetliners are fast, but not the fastest. They fly all the time and spend their lives almost entirely flying. Fighter jets spend most of their time on the ground. In other words, just like the cheetah, they are mostly at rest. Lions spend most of their time sleeping. House cats spend most of their time sleeping. Yes, all of them are fast, just like the sprinter in the 100-meter race.

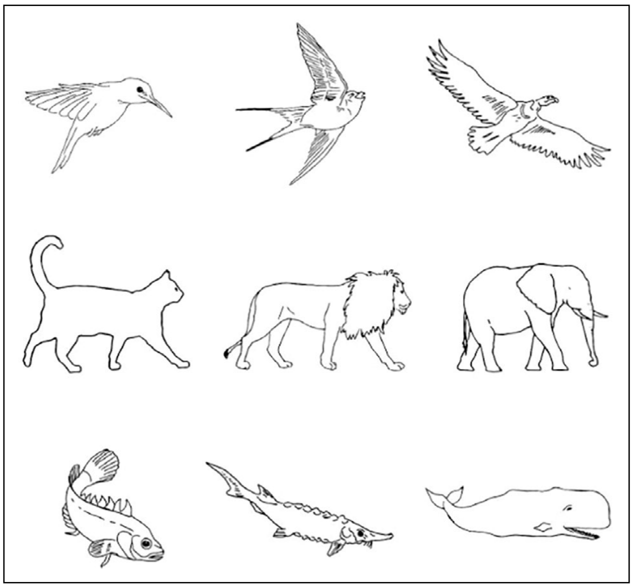


Figure 7.

Diversity is everywhere. No one would confuse the hummingbird with the condor, and the cat with the lion. Diversity has its own physics, and if the physics is known, the diversity can be predicted. This idea becomes clearer by looking at Figure 7, where I drew all the animals the same size. Comparing the cat with the lion, we notice that the cat is mostly belly, with small legs. The lion is showing longer legs and less belly. The elephant is even more exaggerated in the direction toward bigger legs. With physics and the mechanics of the lifting organ (legs for runners, wings for fliers, undulating tail for swimmers), the periodically flexing lifting organ calls for this relationship between the size of the lifting organ and the body size of the mover: relatively bigger motor organs on bigger bodies.

I continue with examples of artefacts, with reference to the need to cool a finite volume. Figure 8 shows a finite volume that generates uniformly a fixed rate of heating. This volume is populated with objects (vertical plates) that are generating heat. The drawing has one degree of freedom: the spacing between the staggered vertical plates. Three designs are shown. The one on the left has large gaps, which means fewer hot plates. The one on the right has many plates and tiny gaps. Of interest is how hot the plates get. Clearly, they are hot on the left and hot on the right. The middle design shows the coolest. This is the discovery that comes from having endowed the drawing with freedom to morph. And so, the recommended spacing, or the recommended number of plates, becomes the secret worth knowing.

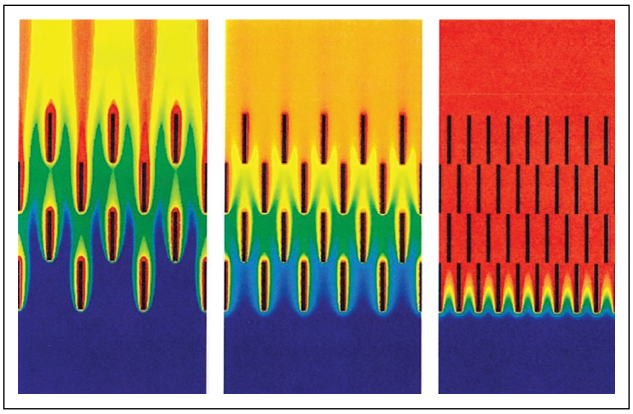


Figure 8.

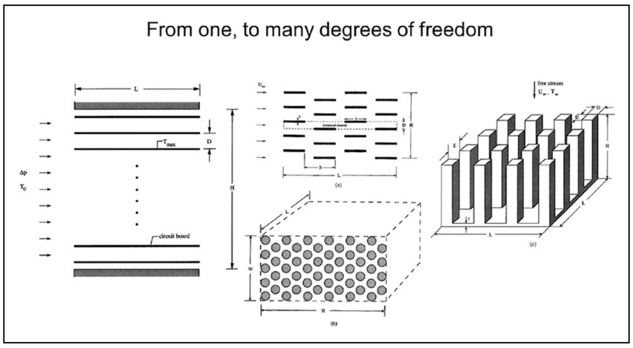


Figure 9.

This secret has been carried in many directions during the past two decades. From left to right in Figure 9, the designs point toward more than one degree of freedom. The design on the left is the same heat-generating package cooling problem as in Figure 8, this time cooled by forced convection. The staggered-plates design has more than one degree of freedom, because free to vary are the spacings between plates, and the spacings between the columns of plates. In the bank of tubes in cross flow there are vertical spacings and horizontal spacings. There is also a choice to be made between the patterns, triangular, circular, square, and so forth. The object on the right in Figure 9 is a heat sink populated by a little forest of pin fins. This is a three-dimensional configuration, to which I will return shortly.

One way to remember the freedom secret of evolutionary design is that the recommended spacing between plates is such that it has the same scale as the thickness of the boundary layers that coat each plate (Fig. 10). The boundary layers are invisible, but they are present in the imagination of the reader who has studied heat transfer from my convection textbook [2]. So, if you know the boundary-layer thickness, you know how to size the spacing between heat-generating components. The design secret is to install the boundary layers in the box in the same way that a child puts crayons in a crayon box.

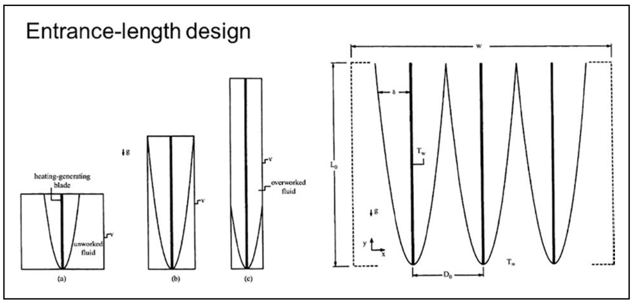


Figure 10.

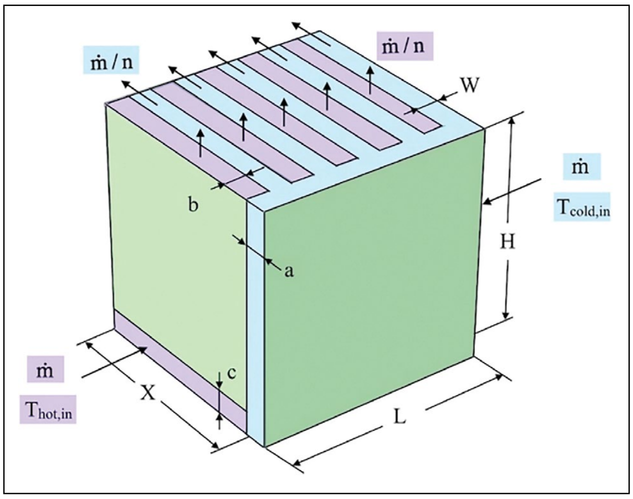


Figure 11.

Another way to remember the valuable design is that the flow in each channel is developing along a length that matches the entrance length of the channel flow. So, another name for this entire design philosophy is *entrance-length design*. This idea has been extended in several directions, including in three dimensions. Figure 11 shows an example of entrance-flow design for a package of two streams in cross flow. The purple stream enters from the left as a sheet and flows upward through five fingers. Each finger has an entrance-length dimension. A second stream enters in blue from the right, and then flows to the left with its own five fingers of entrance length. This is what you can imagine with the concept of entrance length flow architecture.

The left side of Figure 12 shows another concept that comes from having liberated one's thinking in the direction of evolutionary design with freedom. This is the problem that kick-started the field of constructal law and its applications, namely, the problem of the rectangular space with white perimeter on the far left in Figure 12. The rectangular space generates heat uniformly, and the space is occupied by a material with low thermal conductivity. Inserted in that box is a blade with very high thermal conductivity, very much like the rivulet that carries water out of an area occupied by two steep slopes. That is the configuration, and its freedom is in the shape of the rectangle.

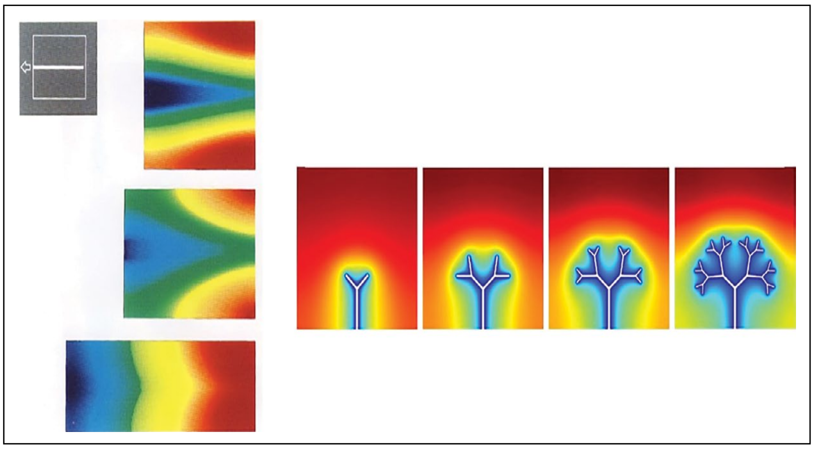


Figure 12.

Next to the leftmost rectangle is a column with three examples of shapes. The bottom shape is shallow, while the top is robust looking. The objective of the entire artefact is to cool the rectangular space the most, that is by avoiding red, which is more evident in the top and bottom shapes while it is less pronounced in the middle shape.

The middle shape teaches one thing: the shape speaks of the balance between horizontal resistance to heat flow and the vertical resistance to heat flow. The balance is also expressed graphically as a finger of a high thermal conductivity inserted in its own glove of low thermal conductivity.

So that's the beginning. If you give this idea even more freedom to morph, as shown in the leftmost of the four branching photos on the right side of Figure 12 by having not only one finger as in the rectangle on the upper left, but three fingers, then each finger comes with its own glove. The smaller ones have thinner gloves, and this way you end up with an arborescent architecture of inserts. Each trunk and branch brings its own sleeve.

In this direction more such add-ons mean more degrees of freedom, such as the angles between tributaries (or branches). So, Figure 12 shows the birth of the philosophy of vascular design, which is the grown-up from the baby in the original problem for heat conduction.

Free architectures have been evolved for convection. Figure 13 is the cover design of the fourth edition of my textbook *Convection Heat Transfer*, followed by pictures of the temperature distribution affected by a cold fluid entering from the center and invading a plate that generates heat uniformly. Two panels are shown on the right of Figure 13, with cooling coming from the right, and the heating coming from the left. In one column the channels are parallel slits, while the rightmost column shows dendritic channels.

Moving on, we reach the question "Why is this important to us?" It is important because it is useful. There is a benefit to knowing what is being presented to you. It is about the rewards from freedom.

Here I present three designs. Figure 14 shows Design #1 of a heat sink with a population of fins on the upper surface of a base layer of high thermal conductivity. The bottom surface of the layer is insulated. The lone degree of freedom of this design is the thickness of the base layer (called δ), which is free to vary.

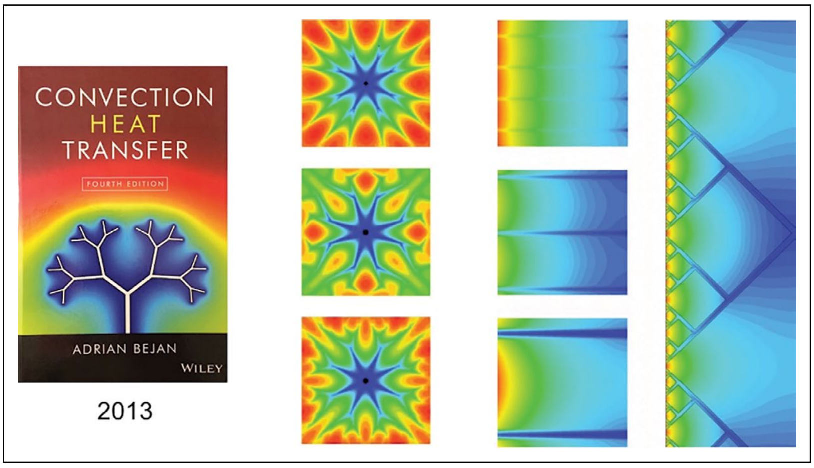


Figure 13.

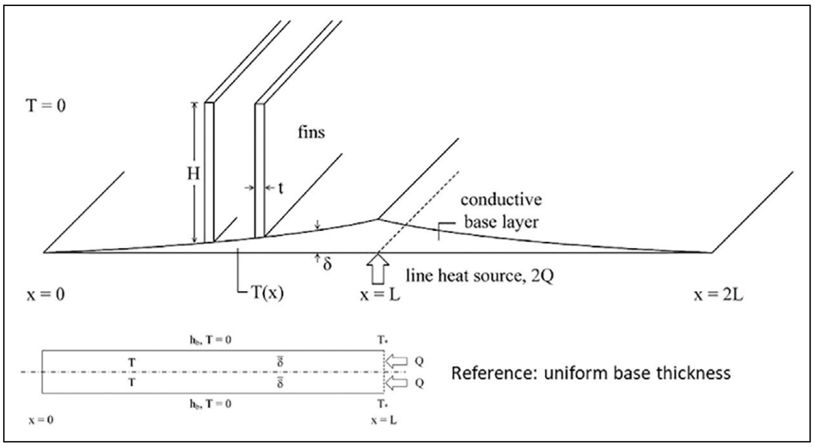
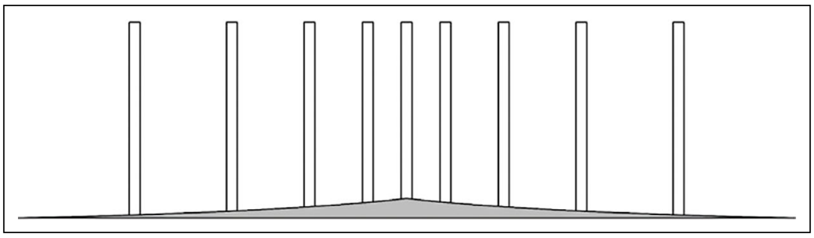


Figure 14.



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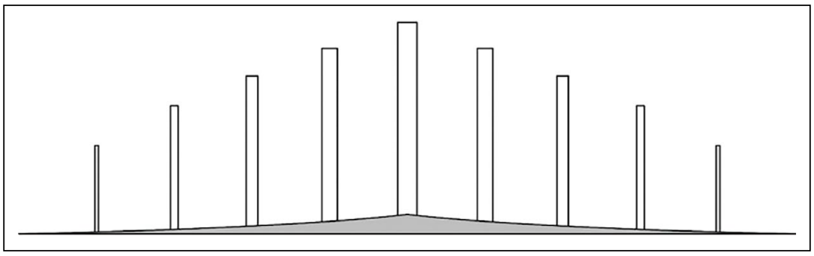

Figure 16.

You can show that if the population of the fins is dense and uniform, then its presence has the same effect as postulating the existence of a constant heat transfer coefficient between the upper surface of the base layer and the ambient fluid.

In the extreme case where δ is constant (as in the upper half of the plate shown at the bottom of Fig. 14), the solution for the peak temperature at the point where the heating is applied is known. Later, I will refer to the bottom shape in Figure 14 as the reference design. The reference design is not one of the three designs that I am comparing here. So, Design #1 is Figure 14.

Design #2 is in Figure 15. This has more than two degrees of freedom, because the first degree of freedom is the variable thickness of the base plate. Design #2 has many degrees of freedom, one degree being the spacing between two adjacent fins.

Design #3 is in Figure 16. The first degree of freedom is the thickness of the base layer, and then every single fin has freedom to vary its profile, meaning the ratio of height to thickness.

In Figures 14 to 16 we have a progression toward more freedom. What is the effect of more freedom? The effect is shown in dimensionless fashion in Figure 17. The peak temperature occurs on the base plate at the point where the heating is applied. The peak temperature decreases monotonically as the number of degrees of freedom increases. This is the conclusion, which means that it pays to endow the flow architecture with the freedom to morph.

Another way to look at cooling packages is to report the heat transfer density in the package versus the length scale (L) of the package, as in Figure 18. If packages are cooled by natural convection (i.e., updraft), as in my first example with spacings (Fig. 8), then the heat-transfer density increases monotonically as the length scale of the package decreases. If the package is cooled by forced convection, then the behavior continues at a faster rate. If the same package is

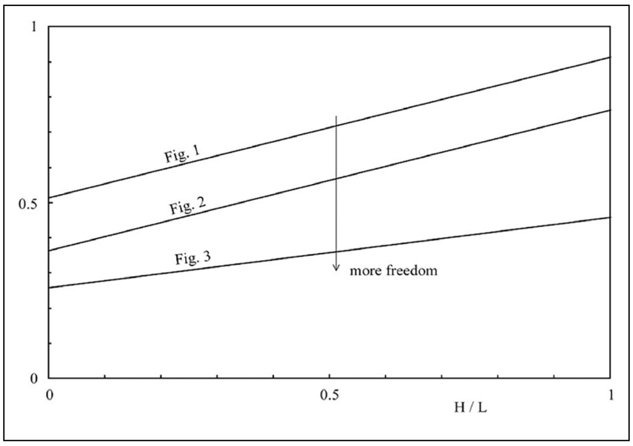

Figure 17.

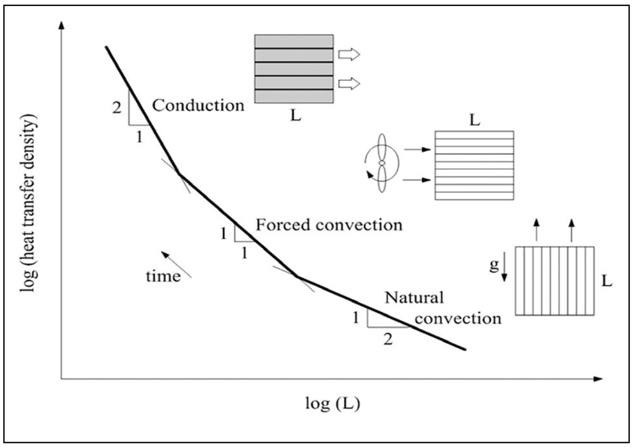

Figure 18.

cooled by solid body conduction, as in newer (and smaller) designs the progress toward greater heat transfer density at smaller scales is even steeper.

With this predictive view of the evolution of cooling technology, we have a crystal ball in which we see the phenomenon of evolution everywhere in nature. Evolution starts gradually, and then...boom!, it gets replaced when the species is 'outcompeted' by a new species. This happens where the slope of the curve in Figure 18 suddenly changes.

A new species that outcompetes an old one doesn't mean that the old species vanishes right away. It means that the landscape populated by these designs becomes more complex in the direction from low heat transfer density to greater compactness and architectures much more effective at removing heat from packages.

Why is it *natural* for the direction of evolution in Figure 18 to be from the lower right to the upper left, toward smaller scales? The answer to this question appears in Figure 19. The component could be the avionics of an airplane, or the heart of a bird. The component could have any size. The component size is the lone degree of freedom that we are discussing.

From thermodynamics we know that a flow component destroys useful energy (or exergy) because of friction in flow passages or heat transfer across finite temperature differences, which are finite because the heat transfer surface pierced by the heat current does not have infinite size. Therefore, when the size of the component increases, the irreversibility associated with the component decreases.

This is an attractive direction to consider. It turns out that this is a mirage because in the same direction (greater size), the weight of the componenet that the big mover must carry increases. Along with that increase comes the proportional increase in the exergy (or fuel) destroyed because of having to carry the component.

The tradeoff between the two dashed curves in Figure 19 proclaims the existence of a recommended component size for a moving system with known body size. This is why big trucks have big engines, and big birds have big hearts.

Why evolution proceeds towards smaller scales has to do with the fact that the flow architecture of the organ improves, from flowing through parallel tubes to flowing through arborescent or tree-like tubes. That means that the descending curve in Figure 19 and Figure 20 has in its

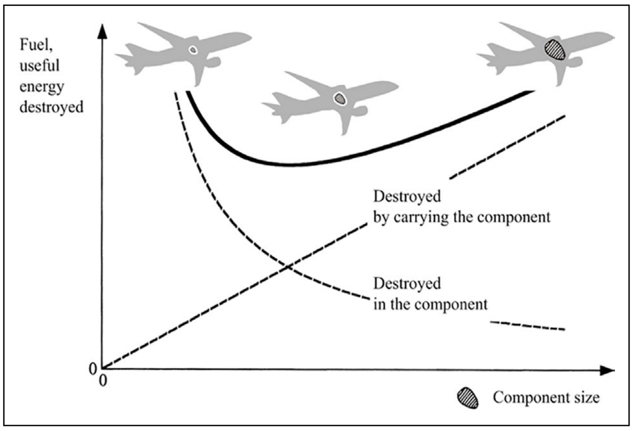

Figure 19.

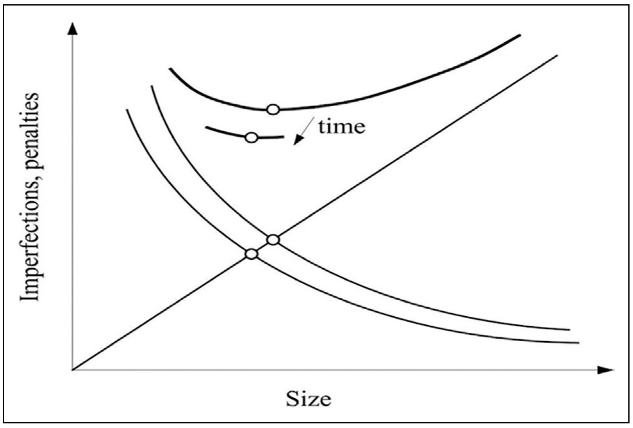

Figure 20.

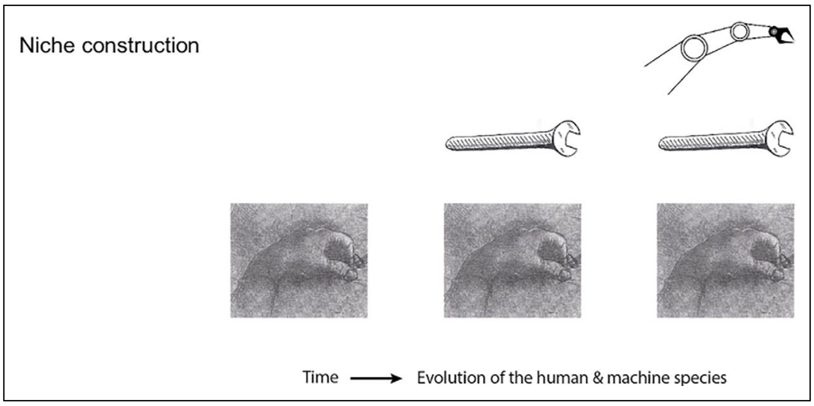

Figure 21.

nature the tendency to migrate downward. The drawing morphs, and the descending curve that migrates downward in Figure 20. The sum of the two curves (the one shaped as a bucket at the top in Fig. 20) has its bottom dropping and migrating to the left toward smaller sizes.

In conclusion, the phenomenon of *miniaturization* in the evolution of technology is predictable. The emergence of smaller components in movers of finite size is natural because the movement of the big (the whole) is facilitated more. Freedom at the level of component evolution translates into rewards for the movement of the whole.

The whole is the beneficiary of all the designs that inhabit it. This is the reality shown in Figure 21 with the image of the naked hand on the left, then the naked hand with a nature-inspired tool (in the middle), and finally the naked hand with the old tool as well as the future tool generated by the human mind.

In evolution what works is kept. The wrench did not make the naked hand obsolete. The 'intelligent' arm will never make the plumber's wrench obsolete. Again, in evolution what works is kept.

The diversity that I illustrated is not random but organized into hierarchies. We get this idea by looking at anything, anywhere. Figure 22 shows the population of models of airplanes versus the year when each model was adopted. The ordinate shows the size of the flying body. The population of models resembles a mountain the crest of which is rising in time. The biggest models are joined by even bigger models. But that's the trivial observation.

The subtle observation is that at any time the new models are arriving in all sizes, from small to large. The new models that arrive are such that the small are many and the big are few. This organization of the diversity is called *hierarchy*.

Hierarchy is evident if we look at all the fliers, beginning with the insects and the birds. In a two-dimensional logarithmic plot of population size versus body size there is a rough straight line that descends from the many small to the few large. In other words, design in nature (i.e., the

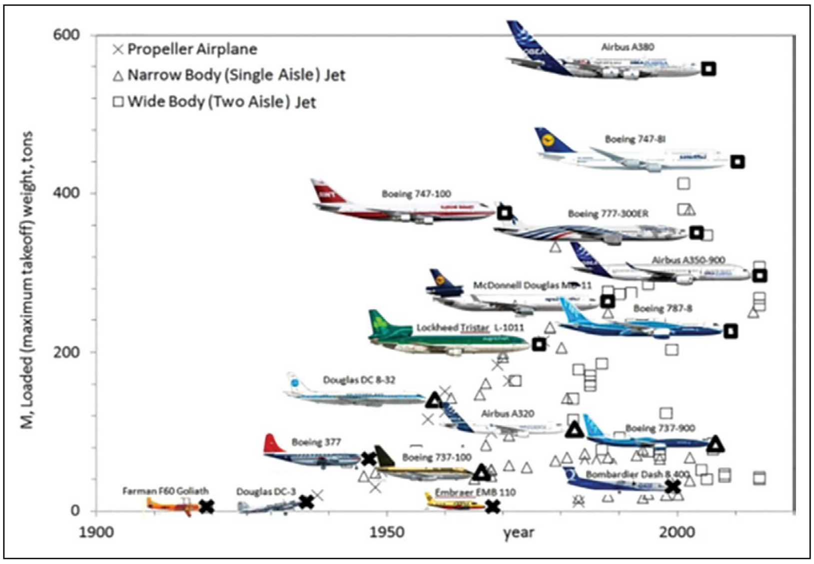

Figure 22.

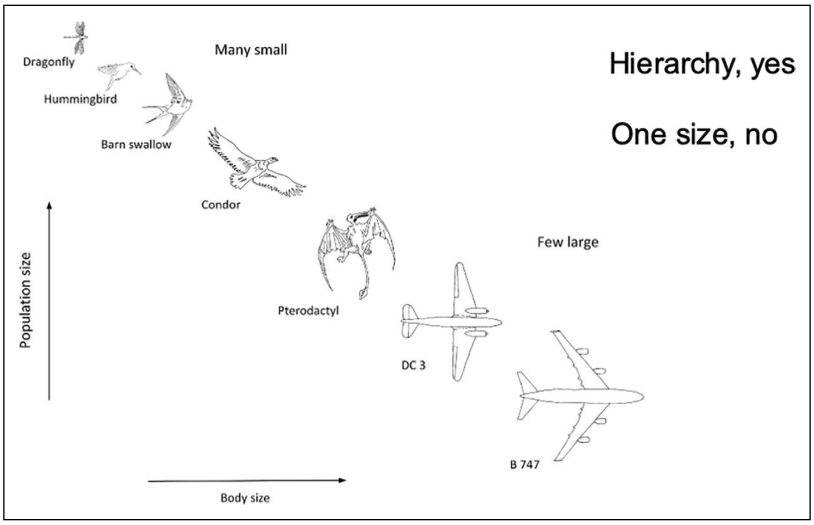

Figure 23.

coexistence and organization of flow designs) just happens, as shown in Figure 23: hierarchically, not in one size.

Why is this? Once again, because of physics. The answer comes like a one-two punch in boxing. The first punch is economies of scale. The top-left detail in Figure 24 shows it as one stream of water that flows through two parallel pipes of equal size. The same stream flows more easily through a single pipe that is more voluminous, i.e., through a single pipe that has the same volume as the original two pipes. The change in flow configuration toward easier flowing is from two pipes to one pipe. That is *economies of scale*.

You can solve the equivalent problem by thinking of two barges on a river, which are being pulled against drag. The comparison is between two barges loaded with coal versus a single barge that is bigger and carries the total load of the first two. You can show that the power required to drag the big barge is smaller than the power required to drag the two small barges. So, based on physics, the change toward easier flowing is from 2 to 1.

Next, if the tendency in nature is to flow more easily, then why is it (or why was it) that not everything that is moving on the landscape is big? The reason is that the flow on the landscape is not from one point to another point, as in the simplest problems of geometry. It is between one point and an area or a volume. The direction of the flow does not matter. What matters is that the point is one and the area (or volume) is an infinity of points. For a flow to cover the infinity of points, it must have access to smaller and smaller pockets of territory lying between the bigger territories that have been served (or wetted, swept) by the bigger streams, as anticipated based on economies of scale.

This way we arrive again at hierarchy. Another word for hierarchy, or the natural emergence of hierarchy, is organization, the natural confluence and coexistence of living things or moving systems. The bottom photograph in Figure 24 shows seagulls on the roof of a cottage on the seashore, facing the breeze. They are doing three things: First, they come together. Second, they face the wind the same way.

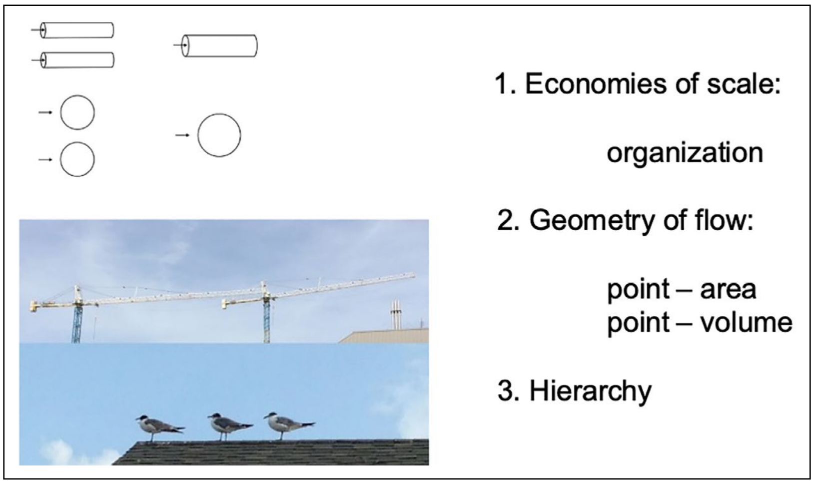

Figure 24.

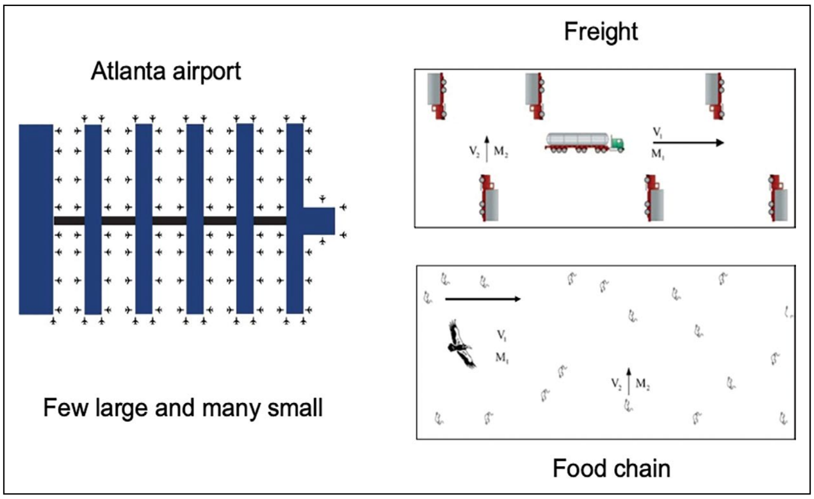

Figure 25.

Third, they space themselves such that the ones in the wake have the same spacing as the vortices in the turbulent wake behind each body. This means that each of the trailing birds is feeling a relative push from behind from the big eddy that was swept downstream. The push from behind makes the trailing bird a lazier worker in its legs, because the bird has to do less work to stand up straight in the wind. The cranes in Figure 24 are oriented in a strong breeze when not working. The 'beak' of the crane is the end loaded with the counterweights, and it is oriented the same way as the beak of the bird.

Hierarchy, organization, or inequality is on display everywhere. Figure 25 shows the movement of people on areas such as the Atlanta airport. There are few large movers and many small movers. The big mover is the group on the train, while the many smaller movers are the pedestrians on the concourses.

Atlanta Airport is an icon of the natural emergence of the city block, with walking perpendicularly to the smallest alley. Freight on a larger area moves and evolves the same way. The same freight is being transported on an area by a few large trucks and many smaller trucks that travel transversely. The food chain is the co-existence of a few big movers with very many small movers that cover the area and move perpendicularly to the big.

The biggest example of hierarchy emerging naturally on Earth is the movement of humanity. Air travel 20 years ago is illustrated in Figure 26 in terms of the measured condensation trails behind all flying aircraft. The red is the heart, and the whole globe is traveling in both directions, to and from the heart.

The global movement is hierarchical. This means that the fuel consumption is hierarchical as well. This hierarchy was not dictated by the general secretary of the Communist Party. It happened naturally. With this idea we can now admire another version of the facts: wealth hierarchy in Figure 27.

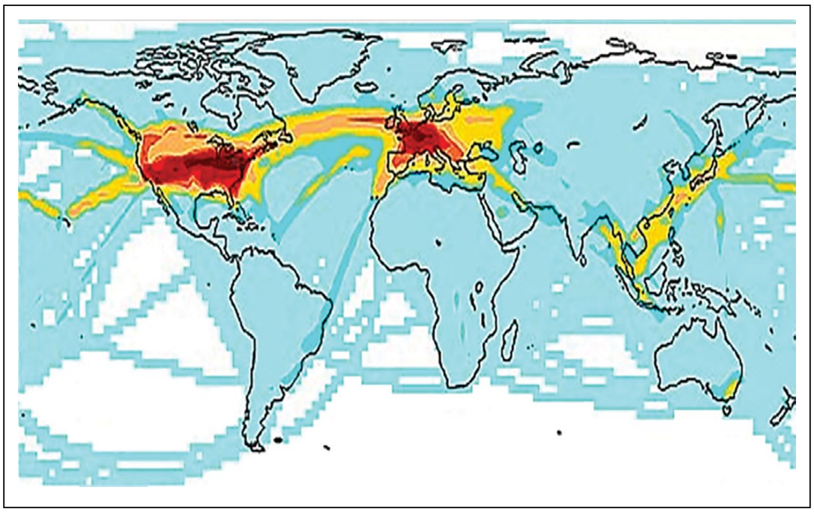

Figure 26.

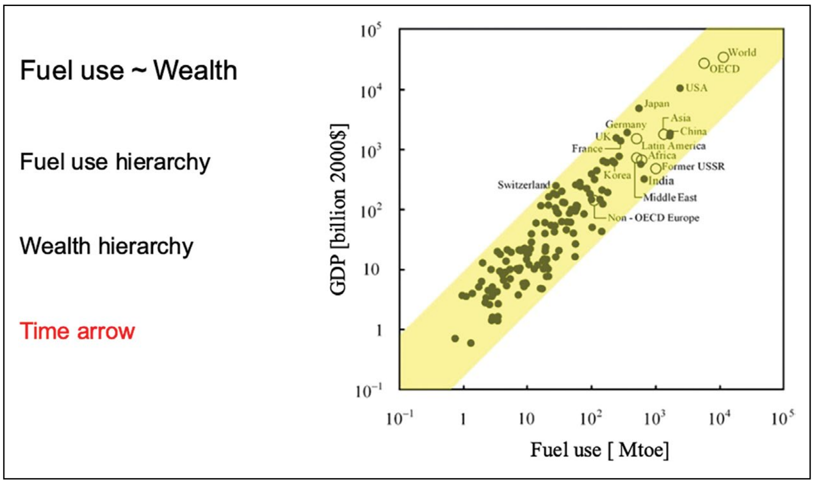

Figure 27.

The physics of economics comes hand in hand with the technology that drives our movement on the planet. Fuel is being burned, from fire and engines comes power, and from power comes movement. Figure 27 shows that the annual fuel use is essentially proportional to the annual wealth known as gross domestic product (GDP). There is a rough 1:1 proportionality between annual fuel use and annual wealth.

We have already established that fuel use emerges hierarchically. This means that the distribution of wealth on the globe is hierarchical and natural as well. The natural phenomenon that gave birth to hierarchy in air travel is the same physics that makes the world hierarchy unstoppable on the globe.

An important feature of Figure 27 is the time arrow of the movement of all the dots that occupy the yellow band on the diagonal. All the dots are racing upward. Government reports every year, regardless of country, are about greater wealth or increased GDP for their populations. That means a necessary annual increase in fuel consumption.

This brings us to the concluding idea, which is that science, as a construct of the human mind and an empowering construct, is itself an evolutionary design evolving in the direction of time just illustrated in Figure 27.

The evolution of thermodynamics during the past 200 years is a good example. From its origins as caloric theory and mechanics, 150 years ago the science evolved into thermodynamics (Fig. 28). Today, evolutionary design has joined and empowered the discipline.

Designs of flow and movement are responsible for the thickness of every single thermodynamics book. The thermodynamics book is about contrivances that have been getting better over time, techniques for producing more power from fire, or producing heating and cooling from that same fire. Their drawings are in the books, and they have been evolving over time. And now, with these three streams (caloric, mechanics, evolution) on the fertile ground of human ingenuity we have thermodynamics that is much better positioned to advance forward.

The evolution of science teaches one more lesson. The path to better science is punctuated by individuals and their ideas. Their names appear in the better books that have been written. The places where the ideas were produced are places where individuals were not only free enough to move, to talk, and to speak but also wealthy enough to move, talk, speak, write, and publish. In particular, these are places where individuals were encouraged to question and come up with ideas.

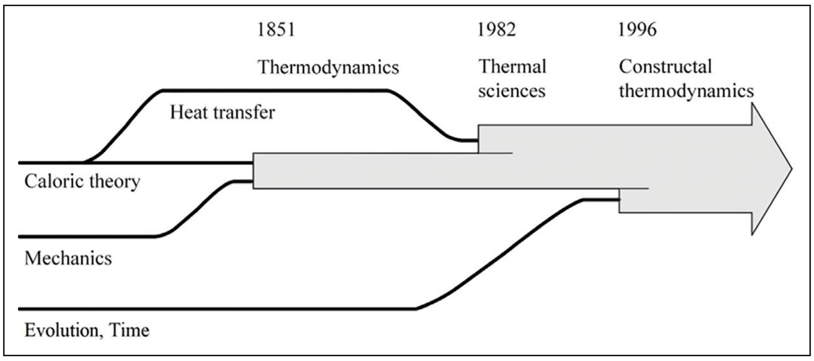

Figure 28.

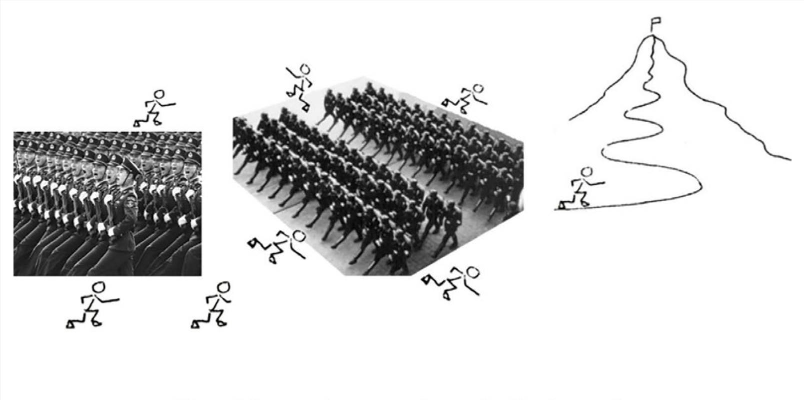

Figure 29.

So, from left to right in Figure 28, the evolution of science speaks of the importance of freedom in the march toward performance of any evolutionary 'live' design.

Individual freedom is the secret of how science evolves and becomes more useful.

DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

TO LEARN MORE:

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