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THE GENESIS OF THE CONSTRUCTAL LAW AS A SCIENTIFIC REVOLUTION

Jack CHUN

The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

E-mail: jack.chun@polyu.edu.hk

Abstract. This paper uncovers the genesis of a scientist's discovery of the constructal law as a scientific revolution from its fermentation to the official formulation. Exploring different models of creative discovery, I reconstruct Bejan's discovery process, documented in his two books [1, 2], as a case study. I conclude that it is illuminative to decipher the subjective dimension that underlies the objective formulation of the law, where something crucial, called the chance-constraint, can be identified, which has been activated in Bejan's personal history long before the scientific law was officially formulated by him.

Key words: Adrian Bejan, Constructal law, Psychology of science, Scientific revolution, Thomas Kuhn, Dean Simonton

1. INTRODUCTION

The emergence of a physics law is often a fascinating story to tell. This is particularly true when the physics law goes beyond existing scientific paradigms in such a way that it demands a re-conceptualization of the nature of the physical world. The constructal law is a case in point, which reads, "For a finite system to persist in time (to live) it must evolve in such a way that it provides easier access to the imposed currents that flow through it" (Bejan [1, 3]). This law applies mathematically without distinction to the objects (or currents), insofar as they are moving. It predicts the patterns of movement of both animate and inanimate objects in terms of their design architectures naturally generated by the flow for their easier access, such as the S-type curve or the hierarchical order of the arrangement of objects. Examples of the "currents" include river currents, vehicles, animals, technologies, humans and anything acquired by them when they move, like knowledge and wealth. The trajectory of human movement, which is typically considered as "free" (including the flow of human knowledge), is now considered as predictable under a physics law. This unification of the predictive power over animate and inanimate objects in one physics law demands one to massively reconceptualise the relationship between physics and the evolutionary movement of everything in the universe. It revolutionizes our conception of the scope of applications of a physics law. In short, a scientific revolution has been emerging. How did this happen?

2. FROM EUREKA TO A PHYSICS LAW

The interesting story about the discovery of the constructal law started with the conference Bejan attended on 24 September 1995, which was his birthday [1, 14]. At the age of 47 as a mechanical engineering professor, he had brought his own seventh engineering book [4] to the international conference on thermodynamics where the Belgian Nobel laureate Ilya Prigogine delivered a pre-banquet talk. In the talk, Prigogine "asserted that the tree-shaped structures that abound in nature – including river basins and deltas, the air passages in our lungs, and lightning bolts – were aléatoires (the result of throwing the dice). That is, there is nothing underlying their similar design. It's just a cosmic coincidence." Bejan claims that his "work took a fateful turn" when he listened to Prigogine's talk. "When he made that statement, something clicked, the penny dropped. I knew that Prigogine, and everyone else, was wrong . . . In a flash, I realized that the world was not formed by random accidents, chance, and fate but that behind the dizzying diversity is a seamless stream of predictable patterns."

This interesting recollection raises two questions. First, why did Adrian Bejan, and nobody else, have this sort of discovery at that point. What special experience might have happened to him that it would be he, not anybody else, to discover the law at that historic moment? Second, Bejan's insight came up as a flash, a click in a split second. It was unprepared and unpremeditated, at least at his conscious level. But how could *that* happen?

3. THE ANSWER SEEKS THE QUESTION

To begin with, Bejan's case might be compared with Archimedes' discovery, as the legend goes, of the principle of buoyance. In *De Architectura* (Book IX, Chapter 3), Vitruvius writes of Archimedes that he was ordered by the king to figure out whether an allegedly golden crown is made of pure gold. After a long deliberation period, one day Archimedes jumped out of the bathing tub after seeing the watering overflowing from it as the result of his sitting down in the bathtub. And he yelled in Greek, *heureka, heureka.* [5, 43–44]

Now, if we compare Archimedes' experience with Bejan, we see that both got some eureka experience, though it seems that only Archimedes also got euphoria on the spot. The point to note here, however, is the ***difference*** at the level of conscious attention that had been paid to the problem prior to the discovery of the solution. Archimedes was ordered by the king to check the purity of the golden crown. He had been totally absorbed in the reflection on the targeted puzzle for a span of time, including his favourite bathtime for deliberating on mathematical problems [6, p. 45]. The facts suggest that the problem was clearly identified before Archimedes started to look for the solution.

Bejan's case is different. The constructal law was not conceived as a solution to any identified puzzle *before the eureka occurred*, because the question had not yet been explicitly posed by anyone yet, not even by Bejan until then. In response to Prigogine's talk, Bejan was literally hit by the idea of the law when he was for the first time to hear Prigogine's talk.

This account, however sketchy, is philosophically important because it does *not* fit in with the influential theory of Thomas Kuhn [7], who tries to account for the paradigm shift as a scientific revolution due to the awareness of the accumulation of irresolvable anomalies of the old paradigm in the scientific community. In Bejan's case, no anomaly has been detected in the scientific community as such. To the contrary, the scientific community was complacent about the conventional assumptions. Instead of being proposed as a solution to an identified problem (or what Kuhn calls "anomalies"), Bejan's idea is more akin to a research programme self-generated (unconsciously from his personal history, as we will see below) that would eventually precipitate a radical conceptual change in physics.

The difference between Archimedes' and Bejan's discoveries can be further explained in terms of the distinction between pseudo- and genuine serendipity [8]. *Pseudo*-serendipity happens when the solution is "accidentally" found in response to a problem identified by the scientist who has already consciously focused on it in reflection. Archimedes is a case in point. On the other hand, *genuine* serendipity happens when the scientist bumps into a solution to something which has never been consciously identified as a problem at all, until the discovery of the answer and the question are made almost simultaneously. At this point, B. Nalebuff and I. Ayers' analysis [9] of creative thinking in general is highly relevant. They argue that the creative answer might ***precede*** the question as if the solution were seeking out the problem. Bejan's discovery belongs to the category of genuine serendipity. I will explore this question in the next two sections.

4. SIMONTON'S DARWINIAN PERSPECTIVE OF CREATIVITY

Dean Simonton [10] advances a Darwinian theory of creative discoveries. According to this model, successful scientists with impactful discoveries typically go through the so-called *variation-selection process*. By this, he means that eminent scientists typically generate a huge number of offspring (publications) with *ideational variation* for their entrance to the hall of fame in history. Simonton's model is Darwinian because, as nature always blindly lets the fittest survive, the creative scientist would also succeed "blindly" by chancing on the "fittest" publications for the reception of the scientific community from his/her large pool of publications. The more offspring the higher the chance for the scientist to adapt to the varying conditions of the selection process. Yet, what is considered as the fittest offspring/output is something, on this model, quite unpredictable to the scientist and is highly contingent on the intellectual climate and standards adopted at that time. There are just so many variables for the development of the intellectual standards that the factor of randomness, Simonton argues, would dominate the scene all the time.

Simonton further holds that for scientists to be successfully impactful they have to be prolific and productive. Nature, or the scientific community, will do the rest for "blindly" admitting the best at the time. In addition, what is really needed for the fittest to survive would not (and need not) be all (not even the majority) of the publications of the creative scientist for him/her to be recognized as eminent. A few "fittest" publications would keep the scientist's name shining in history. For example, Einstein in his lifetime published around 300 pieces of scientific works (based on Schilpp [11] and Calaprice *et al.* [12]) out of 80,000 existing records of his manuscripts and correspondence (see Einstein Papers Project [13]). Only a handful of his academic publications were considered epoch-making while others were hardly read by the general scientific community. But this is already more than adequate to single Einstein out in the history of science as exceptionally creative and successfully epoch-making.

Let's go back to the conference in 1995 when the idea of constructal law first flashed across Bejan's mind. By that time, Bejan already published 7 books and 228 peer-reviewed journal papers [14, 15]. This prolific productivity continues as a regular pattern in his career. By 2017, he has published 30 books and over 600 peer-reviewed papers, and already been rated as one of the top 100 highly cited in all engineering research in 2001. This outstanding output record clearly satisfies one of Simonton's Darwinian requisite conditions for the recognition of the scientist's successful creativity in science.

But there are limitations of this Darwinian model. Simonton admits that this model could not predict or explain what exactly would be produced or the exact time when the epoch-making product will come out from the history of the prolific scientist. Much would depend on chance. He claims, "The broad outlines of genius and its products can be explained and predicted with commendable confidence, but the minuscule names, dates, and places are left in the whimsical hands of historical chance" [10, p. 189]. But the qualifications he then makes on the same page seem to cause some tension within his theory: "Of course, to note that chance participates so conspicuously in the making of the creative product is not tantamount to asserting that genius is random. The effects of chance are constrained". So, apart from chance-elements, there should be chance-constraints. It is the interplay of these two that could fully account for what has really happened in any of the creative discoveries in science. In his later work [16], Simonton basically delves into the possible constraints of chance, specifically in science. One of such chance-constraints is the scientist's character trait. Another is the personal history. In the next section, I will explore these chance-constraints in Bejan's case.

5. THE GENESIS: WHAT HAPPENED ON 24 SEPTEMBER 1995 (AND BEFORE)

What sorts of personality traits, abilities and experiences did Bejan possess, as documented by himself, that might help explain (by imposing the constraints on chance) that it was more likely for him than any other scientist to discover the law at that point, assuming other candidates under consideration also sharing the same prowess in engineering knowledge and mathematical skills?

I want to single out two interesting aspects of his life experience [1]. First, he was a member of the Romanian national basketball team before he became an engineering professor. This indicates his top capabilities in the sport that implicate a certain type of intelligence in physical movement. Howard Gardner [17] calls it the bodily-kinesthetic intelligence, and Robert and Michele Root-Bernstein [18] name it the ability of bodily thinking. At the same time, Bejan displayed an early interest and talent in drawing and his parents had sent him to an art school in Romania. This interest in drawing has never ended. In fact, some of the pictures in his books were drawn by him. In his discussion of the constructal law, he keeps referring to his previous experience of drawing at different stages. In [1], he uses the term "drawing(s)" for 56 times. He even claims, "The constructal law is also a way of seeing" [1, 7]. That is quite a remarkable statement. For the type of artistic intelligence displayed by Bejan, Gardner would identify it as the spatial intelligence, and Root-Bernsteins as the imaging abilities.

What can one make from these two types of additional talents for one who is good at mathematics? First, let's begin at the general level. It is illuminating to look to Csikszentmihalyi's account [19] of the psychology of creative individuals. He notes that creative people, different from the non-creative, tend *not* to be dominated by unitary dimensions of personality (or a group of dimensions that the tradition would estimate as of the same conglomeration) but "seem to harbour ***opposite tendencies" as integral to their personality***: they would have both opposite personalities integrated as one in the same person. The ten pairs of opposite personalities or personal styles of creative individuals, as noted by him, are: (1) energetic/quiet; (2) convergent/divergent in thinking; (3) playful/disciplinary; (4) imaginative/with a strong sense of reality; (5) extrovert/introvert; (6) humble/proud; (7) masculine/feminine; (8) traditional/conservative; (9) passionate/ objective; (10) with the opposite tendencies to expose themselves to pain and enjoyment.

The possession of these opposite personality traits reveals that the successful, creative individual enjoys a special perspective and thinking style that other people seldom do. Such a dynamic personality would favour adaptability and flexibility in thinking by attacking the problem from different combinations of angles, and the readiness to think out of the box, whatever box (discipline) is in question. If Bejan's sophisticated interests in artistic drawing and sport display the energetic and quiet personalities respectively (or even the extrovert and introvert personalities for that matter), he clearly fits in with some of the crucial traits of creative personality. And, based on my personal acquaintance with him, I suspect that he would possess more, if not all, of such polar pairs of personalities as unified in the same person. There is a reason why he observes of himself that he is "able to see what others had missed." This is the general point I want to make about the especially advantageous position Bejan occupies with his dynamic personality.

Now, it would be oversimplification to conjoin the formulation of the constructal law and Bejan's life-long, cultivated interests in artistic drawing as the same type of spatial intelligence and simply from this to conclude that it was Bejan to discover the law in 1995. For one thing, the formulation of the law requires, as Gardner [17] would claim, the logico-mathematical intelligence and it is not yet clear how this figures in the explanatory account of his discovery of the law. For another, it remains to see in more detail how the possession of these diverse abilities (of the visual art and mathematics) can exactly better explain the scientific discovery.

A better way of examining the case would first start with an important feature of creative thinking, be it called associative basis by Mednick [20], bisociative thinking by Arthur Koestler [21], alchemy by Annette Moser-Wellman [22] or combinatorial processes by Simonton [10]. The function of this type of associative thinking is that the creative scientist would combine or relate two remote or unrelated disciplines or skills in the problem-solving process. In history, this combination of unrelated skills or disciplinary knowledge happened quite often for creative geniuses, in science and arts. A famous example is Albert Einstein. When asked how he conducted scientific thinking, he answered, as cited by Brewster Ghiselin [23], that it was essential for him first to have a "combinatory play" of images, of which some are muscularly felt, in seeing and confirming any important ideas. The logical construction in words, which became secondary and ad hoc in importance for Einstein, would come at a later stage. The associative combination of visual images is a signature thinking style of Einstein. His visualizations of thought-experiments famously abounded. Other physicists also have similarly interesting experience. Richard Feynman reported that when he was solving a mathematical equation, he would see individual mathematical variables literally flying around in different colours. What is more, when Feynman studied Euclidean geometry problems, he reported that he "manipulated the diagrams in his mind; he anchored some points and let others float, imagined some lines as stiff rods and others as stretchable bands, and let the shapes slide until he could see what the result must be," as noted by Moser-Wellman [22]. Outside science, even Wolfgang Amadeus Mozart noted that he would visualize the entire musical composition as a static physical statue and see it all at one glance, so that he would *not* hear the musical piece in his imagination successively in parts (as all of us might do), but hearing them all at once, comparable to seeing an object at one glance. He thought that this was the best gift given to him by the Divine Maker [Ghiselin 23].

There is no doubt that Bejan would easily conduct this type of visualization in scientific thinking. In fact, to reiterate, for him "The constructal law is also a way of seeing." Bejan has consistently brought drawing into mathematics, converting drawing as part of mathematics. "I began with pencil and paper. I drew a rectangle filled with circuits in the system." "I called my first drawing the *elemental construct*" [1, 2]. He has a chapter [1] on this *vision* of oneness of objects (animate and inanimate) as the implication for adopting the constructal law. He saw the tree-like patterns generated by the inanimate and animate objects not as a coincidence in the conference in 1995. It is about the structure of the universe. In retrospect, the gap between the two types of objects is *closed* and they are seen as of the same category, united in oneness under the constructal law.

Now, and this is the important point and the conjecture I want to make in this paper, isn't it the case that in drawing there is no need to drive the (ontological) wedge between inanimate and animate objects? Both realms of objects could be portraited in lines and colours just as beautifully as one another. They are on a par, *artistically* speaking. The distinction between the inanimate and animate objects as two disparate ontological categories foreign to each other would be artificial and arbitrary, from an artistic viewpoint. This is exactly one of the embedded points made in Bejan's recollection [1, p. 75] of an interesting anecdote in his heartfelt observation of his father's ingenious solution to the lack of meat in Romania in the 1960's by hatching eggs. Bejan says (with my emphasis added) that, as a teenager, "I started in awe and wonder at the growth that unrolled before my eyes each day, as the vasculature grew and spread tightly on the inside surface of the shell. ***I also noticed that the design I was seeing was the same as that of the river basins on the colored maps I was drawing in school.*** Where the chicken embryo was evolving on the inside of the sphere, the Danube basin had evolved on the outside of the spherical Earth. . . Back then, I considered these similarities cool correspondences, nice ideas."

On the surface, the intended point Bejan makes above is that, back then as a teenager, he did not see the seamless connection between the inanimate and animate objects from a physics point of view. This for sure is true. How could he know the underlying mathematics at that time? But *pace* Bejan, he is wrong to imply that he has no inkling of whatever that might eventually contribute to the discovery of the constructal law. From the artistic point of view he learnt from the drawing school, he should not draw only animate or only inanimate objects. Skill-wise, he need not make such a distinction between the inanimate and the animate objects as if they belonged to different disciplines. What he missed out was not, again in retrospect, the revolutionary picture about the oneness of the animate and inanimate objects in nature but the mathematical skills that he was about to acquire in the USA one decade later. This overriding, unconscious, artistic, unified conception of the world that has stayed with him for as long as he ever got his never-ceasing interests in drawing, I hold, has penetrated his thinking and conception, including the scientific, of the objects, at the unconscious if not conscious level. This should unmistakably have laid the very special foundation for the unique discovery of the epoch-making constructal law: the gap between inanimate and animate objects, which has long been bridged in his artistic heart, should somehow be merged *once again* mathematically in his engineering profession, whereby the ontology of oneness be materialized seamlessly. For this reason, Bejan belongs to the modern renaissance scholars who openly rejects the artificial wedge between the art and science disciplines in the modern university curriculum.

In passing, it is interesting to note that a similar motivation had been shared by another artist-engineer, who was less fortunate than Bejan as he did not have the chance to acquaint himself with the laws of thermodynamics or sophisticated mathematical skills, thereby lacking the requisite conceptual apparatus to complete the mathematical task. And this unfortunate soul was Leonardo da Vinci. According to Wojciehowski [24], Leonardo da Vinci also had in his lifetime "begun to look for the constant mechanical laws and models that applied to all things – organic or inorganic, animate or inanimate. This unity based on motion that he sought to theorize encompassed machines, buildings, the Earth, animals and man." Something more than a chance, which in Simonton's words is the "chance-constraint," is indeed required for the completion of the story of the discovery of the constructal law.

By the completion of his seventh engineering book, coupled with his prior artistic experience and creative personality fostered since the Romania days, Bejan was already in the position of leaping from "the scientific community's conventional wisdom" in grasping the type of answer that would seek out the question simultaneously. The answer could not be fully articulated at the conscious level until the question prompted it. Thanks to Prigogine, his talk has directly precipitated the question in Bejan's mind, to which he should have had the answer ready-made unconsciously at the back of his mind *long ago*. The constraints on chance nicely met with the chance event of the conference, where, unbeknownst to him, Bejan would almost be destined to be the one who would "suddenly" proclaim the discovery of the constructal law.

6. CONCLUSION

History never repeats itself. It is difficult to evaluate the conjectures I have made. So, what conclusion can one draw from all this? I hold that, given the constraints on chance as delineated above, one could at least say that it was very likely that Bejan (and nobody else at that time, on the assumption that his personal experience and talents were unique) would be the one who discovered the constructal law. A still better way of putting this is this: it is ***very unlikely*** that, when everything had fallen into place in just the way they had (that is, at the right time in the right place), Bejan did ***not consciously discover*** (his unconscious discovery of) the constructal law. It is not that it is necessary that he did that at that historic moment. It is only that it is very unlikely that he did not (or would not). The double negation of the last sentence, I trust, reveals something important (the interplay between chance events and chance constraints) that is worth pondering and articulating from the history of scientific discoveries and, above all, scientific revolutions.

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