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CONSTRUCTAL LAW IN LIGHT OF PHILOSOPHY OF SCIENCE

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Abstract. Since it was first submitted in 1996 and later published in an early 1997 issue of the International Journal of Heat and Mass Transfer (Bejan, 1997), the Constructal Law (CL) statement "For a finite-size system to persist in time (to live), it must evolve in such way that it provides easier access to the imposed (global) currents that flow through it." has invited the scientific community and the general public to take a new outlook on the phenomenon of origin and evolution of shapes, forms, rhythms and organization. The original statement has been revised along the years. As new paradigm and language were introduced, questions arose from the scientific community. One of the issues concerns whether the theory was stated according to today's consensual scientific method. In this paper, the Constructal Law is discussed in light of philosophy of science and its adherence to the current consensual scientific method. The falsifiability and testability of CL are addressed. The original statement is rewritten in two complementary hypotheses in order to turn its testability explicit. It is shown that CL and its derivative theories meet the epistemological criteria either in the strict sense of Karl Popper's positivism or Thomas Kuhn postulates of scientific revolutions (paradigm transitions). In addition the origin of the name "constructal" and its contrast to fractal is revisited.

Key words: Constructal law, Epistemology, Falsifiability, Scientific method, Fractals.

1. INTRODUCTION

Constructal Law (CL) was first submitted in 1996 and later published in a 1997 issue of the International Journal of Heat and Mass Transfer [1, 2] with the statement "For a finite-size flow system to persist in time (to live), its configuration must change in time such that it provides easier and easier access to its currents.".

The new idea was that shapes, forms, rhythms and organization are all outcome of one single physics principle that applies indistinctively in the animate, the non-animate and in the human made realms. CL is necessary for it addresses the reasons why design and organization evolve while other theories mostly rely on *ad-hoc* principles or just focus on the mechanisms of how specific designs and organizations occur and evolve [2–7, 23]. CL is meant to be an alternative to plain empirical modeling.

Along twenty years CL has been adopted in many branches of Science (e.g., [8–12]). The Constructal theories provided new outlooks, interpretations and more importantly explanations rather than description to many observed phenomena. In fact CL proposed a paradigm shift [3–5, 7, 8]. Today there are more than 13,000 qualified citations with the entry "constructal" [13]. The field has been reviewed periodically [4, 5, 7, 9, 12, 14, 15]. This paper provides a brief epistemological outlook of the Constructal law. In this brief essay I rely my arguments on the works and visions of those who are concerned with the scientific method and the progress of scientific knowledge, e.g., refs. [16–20]. Kremer-Marietti, Brachta and Dhombres [21] have previously opened that line of debate. They pointed out the virtue of CL being a theory, not a model, and a candidate to be a "law of physics". The discussion presented in this paper covers from the extreme demarcation principle of Popper's *critical rationalism* to Feyerabend's *methodological anarchism*.

The paper addresses the logic of the CL statement, the embodied conjectures and its testability. I revisit the original CL statement and present it in two direct falsifiable hypotheses in order to enhance its testability and meet the most orthodox demarcation criteria. CL can be verified or refuted by anyone who can properly test it. I also explain how this natural law was named "constructal". The paper ultimately shows the Constructal Law statement meets the requirements of contemporary views of the scientific method.

2. ON THE PHILOSOPHIC METHOD BEHIND THE CONSTRUCTAL THEORY

First let us acknowledge that Bejan's statement of the constructal law was a just a hypothesis within a theory, the constructal theory (a hypothesis itself), namely [1-7]:

i. The generation and evolution of shapes, forms, structures, rhythms, i.e., design and organization in nature is a physics phenomenon;

ii. Such phenomenon is the outcome of a principle: the constructal law;

With these two hypotheses and the CL statement comes an embodied set of premises [1–7]:

Flow System: It refers to anything that functions, biotic, abiotic or anthropic, separated from its surroundings through which any kind of flow associated to the system's purposes takes place. "A flow represents the movement of one entity relative to another (the background)" [2]. It however refers to a category of system with same features not to an individual specimen;

Finite-size: The system size is measurable (not infinitesimal, nor infinity) in way the system becomes macroscopic. It has discernible and measurable features;

Imposed currents: Anything that flows, as stated in the "Flow system", that is related to the functions of the system and that can be observed and measured in proper units;

Persist in time (to live): It means that specimens of such flow systems are not "dead" in the sense they are still observable through time and currents still flow through it. Ref. [7] states that "a live system is one that has two universal characteristics: It flows (i.e., it is a nonequilibrium system in thermodynamics), and it morphs freely toward configurations that allow all its currents to flow more easily over time." In the CT paradigm to be alive is more than being in nonequilibrium with the surroundings;

Configuration: A set of discernible and measurable attributes that establish an arrangement of elements, shapes, forms in a particular form, figure, or combination of those and affects the access of the currents by the flow system;

Evolve: Something that undergoes the process of evolution. "Evolution means changes that occur in a discernible direction in time" and it is related to the purposes of the flow system [9];

Greater (easier) access: Easier access to the currents that matters for the flow system to be alive (to be functioning) either within the system or outside the system;

Design: Ref. [9] states design "…is a plan, a scheme, a project with purpose or intention (aim) for an outcome. Design is the arrangement of parts, details, form, and color, so as to produce a complete unit that has purpose";

Time scale: There is implicitly the premise that the changes in configuration are discernible in a compatible time scale in which design evolution can be accounted for.

The two claims of the CT resulted from observations under the spirit of inductivism in the sense that inductive reasoning is the process by which a small set of observations is used to infer a larger theory without necessarily proving it at the moment it is stated. It is a leap, a risk, a scientist takes in the direction to explain phenomena that the prevailing paradigms of science seem to fail to do so.

In his 1996 paper Bejan [1] made use of design of electronics cooling to introduce his theory. He went beyond the technological problem addressed in the paper and took the risk of registering his insights in the old question of the origins of observable "design" in nature and in the human civilizations. Bejan did that instead of playing the so-called Popper's "game of science" which Thomas Kuhn also referred to as "normal science" [18, p. 35]. Kuhn stated it is often unwittingly adopted and it does not question the established paradigms.

Bejan and collaborators have since applied the ideas and the CL hypotheses to a variety of problems (e.g., [1–5, 8–10, 23]). To say the least it has be proven to be an effective method of design [2] – it became indeed a useful paradigm in almost 1900 qualified papers [13].

In order to provide a more conventional framework for CT, Bejan and collaborators also introduced more elements of the established body of knowledge such as Classical Thermodynamics [22], Irreversible Thermodynamics [23] and the accompany mathematics. Bejan argues thermodynamics is the appropriate field to study design evolution as physics (e.g., ref. [15]). By the same token, he also claims CL is a complementary law of thermodynamics (e.g., [15]). In the recent years, the constructal theory has been taken to a higher level of generalization. Now it claims to be a broader paradigm. It is a new way of thinking at everything that "lives" and what "life" itself is [2, 5].

Today constructal theory (and constructal law) is undoubtedly an established field. There is now a network of collaborations with published results [13]. Perhaps is fair to say in the last twenty years CT has climbed the steps of *transitional paradigms* [18], when it is already adopted by some and still refuted by others. One then should question of what is a fair framework to accept or refute CT?

Initially one ought to make sure the CT belongs in science. There are four main schools of thoughts in philosophy of science that deal with *demarcation*, namely, *inductivism* (Bacon), *falsificationism* (Popper) *transitional paradigms* (Kuhn) and *methodological anarchy* (Feyerabend), e.g., [16, 17].

The most rigorous school of demarcation is provided by Popper's *critical reasoning* or *falsificationism*. Essentially he proposed all scientific hypothesis, proposition or theory must be *falsifiable*, which is the inherent possibility of a theory of being logically tested (*testability*) or the possibility to prove a theory to be false. In sum, a *true* scientific theory must provide the opportunity to be refuted in the theory's statement. Most of today's "good" scientific experiments adopt the paradigm of *falsificationism* (e.g., [16, 17, 20]).

The two main statements of the Second Law of thermodynamics are good examples of falsified statements (e.g., [6, 9]):

Clausius: *No process is possible whose sole results is the transfer of heat from a body of lower temperature to a body of higher temperature*.

Kelvin: *Spontaneously, heat cannot flow from cold regions to hot regions without external work being performed on the system*.

They were stated in XIX century. The negative tense of those statements helps design experiments to test the validity of the claims. However unlikely, it is possible that one day a test will show Second Law to be false or not *universally true*. All that it takes is one single false outcome of test.

Falsificationism has been criticized for being too limiting and also that there were instances in history when scientific breakthroughs took place without following the *good science* consensus of its time [18, 19]. The excessive positivist and dogmatic nature of *falsificationism* has been highly questioned (e.g., [16–19]). Is there *scientific truth*? And if there is, is *falsificationism* the only proper method to find them? Can theories be truly verified? What is a proper test?

Perhalps all scientists can do is to propose and test theories hoping to make contributions. In any case, proper testing would require *verification* or *confirmation*. *Verification* would be the ultimate test of a claim. It is a rigorous way to classify a theory valid or invalid. Nevertheless, Rudolf Carnap proposed confirmation instead of the plain and absolute verification of claims. As long as a theory passes proper testing it goes confirmed (e.g., [16, 18]). In confirmation theory there still remains to establish what counts as evidence, how well evidence supports a claim and how much evidence is needed to support a claim [16, 17, 19, 20].

I argued that Bejan made use of *inductivism* to propose his theory in ref. [1] and created a *transition of paradigms* as opposing to following the *normal science* [18]. Constructal theory is so general it is hard to conceive tests in short time. Bejan took the leap of faith out of the orthodox Popper's *critical reasoning*. He probably just realized that *normal science* or the *game of science* would not allow the investigation to go further.

There is a school of demarcation that proposes full freedom. The so-called *methodological anarchy* was set forth by Paul Feyerabend in his book "Against Method" [19]. According to Feyerabend there should not be a "scientific method" as a doctrine or as a rule. The continuous quest for answers will filter what works and what does not. Strict rules will only inhibit the progress of science. Furthermore excessive weight on evidence may be flawed because evidence may be contaminated. One should not discard theories because it is hard to be *tested* or *verified*. Good examples of theories that otherwise would have been discarded at the first moment are the statements of the second law of thermodynamics. Those verbal propositions turned out be one of the foundations of classical thermodynamics.

Bejan and Lorente consider science a construct of human civilization that itself follows the constructal law: "Science is an evolutionary design in which what we know – what is true, what works – becomes simpler, more accessible, and easier to teach." Perhaps it was not accidentally Bejan closed his last review paper [15] saying, "Science is self-correcting".

The present arguments do not claim "anything goes" but the understanding that CL and CT were not intended – and probably should not have – to meet the orthodoxy of restraining doctrines.

It seems there is not, perhaps there must not be, a strict rule for a fair framework of *testability* and *confirmation* for CT, CL or any other theory that presents itself as candidate to explain the observations of forms, shapes, design, rhythms and organization that are ubiquitous in *nature*.

Still, in the next section I show how CT and CL fit in the school of thoughts of scientific method.

3. HOW CONSTRUCTAL THEORY AND CONSTRUCTAL LAW MEET THE REQUIREMENTS

By now it is fair to say the statement of the constructal law as well as the constructal theory are in conformity with *inductivism*, with Kuhn's *paradigms transition* and with *methodological anarchy* in science. There remains to address how CL and CT fit in Popper's *critical rationalism* or *falsicationism*.

Published criticism on CL and CT have been based on arguments comparing the performance of specific designs, that the law is not precise neither mathematically sound, and that it does not follow the most accepted *doctrines* of the scientific method in physics. Some of those arguments have been addressed (e.g., [4, 6, 7]). Some of that criticism came from advocates of competing theories for particular fields. Most criticisms have also been made in websites never in the scientific literature. The legitimacy of those critics, most often anonymous, is highly questionable.

Many of the theories based on the constructal law use *deductive reasoning* (e.g., [1, 2, 9, 10, 15]).

Constructal Theory is not modeling even though one can build models from it. It is the conjecture that supports the idea that any occurrence of organization and design is the result of a sole natural principle. And being so, it is fair to say it is part of physics as we know today. CL was proposed as law from the start [1] and later argued as such by Kremer-Marietti [21] because it could not be deduced from any other known first principles. Therefore it remains to be shown whether CL and CT can be tested as a scientific theory following the prevailing practices or if it is just taking the long path of paradigm shift.

The first part of the constructal theory is: (i) *The generation and evolution of shapes, forms, structures, rhythms, i.e., design and organization in nature is a physics phenomenon*. The validity of this conjecture will depend more on the meaning of the terms *design*, *organization*, *nature* and *physics*. The two additional embodied premises are the following (e.g., [5, 7, 9]):

Nature: comprises of the so called natural world in the ordinary sense and the world built by human civilization;

Physics: it means the knowledge of nature. The branch of science that studies the observed natural world. Alternatively the field which goal is to analyze and understand the natural phenomena of the universe.

One can agree or disagree with a statement only in view of its premises. If one takes the conventionally and often excessive *positivist* mindset of physics, at first one tends to disagree with CT statement (i) since there is no formula with physical quantities in conventional physical units.

The CL statement (ii) [1, 2, 5, 7, 15] can be rewritten to meet falsifiability requirements as Popper proposed. Two distinct logical parts can be identified and will be treated separately. First, that design changes over time (H1), and second, on the direction and conditions those changes take place over time (H2). It thus follows that a sequence of falsifiable hypotheses can be set forth. And if both of them are falsifiable, hence the main CL statement can be false. CL is thus falsifiable.

The first hypothesis (H1) considers the established premises of finite-size system, flow system, freedom to morph, life, imposed currents, changes over time and design in physics:

H1: *It is impossible for the design of a living finite-size flow system with freedom to morph to stay unchanged over time when currents are imposed through it.*

One credible evidence of the possibility that a system design remains unchanged under such conditions will disprove H1, then H1 will be false and ultimately CL will be false. CL is thus *falsifiable*. A proper test condition requires a reasonable time scale.

Confirmation, *sensus* Carnap, tells us H1 will be considered valid whenever the observed data matches the theoretical predictions of prescribed properties. In this case, they are the discernible and measurable geometric features, rhythm, etc. If the claim is confirmed extensively and long enough, the scientific community adopts H1 as a paradigm and universal as seen in other historical instances (e.g., Second Law).

H1 is in "negative" tense as the classic statements of the second law of thermodynamics. Worth noting Clausius and Kelvin took the risk of not testing all possible imaginable and feasible situations that second law covered. That so because it covers everything and it would be infeasible. Nonetheless both statements are *falsifiable*. It suffices to find one single observation that contradicts their claims to turn their statement of the second law false. The second law has been tested exhaustively, always confirmed and it has become one of the pillars of physics. The hypothesis H1 can now follow the same course.

The second part of the CL statement deals with the direction design changes take place:

H2: *It is impossible to a living finite-size flow system persist in time when the designed changes that occurred progressively impede the access to the imposed currents that flow through it.*

The falsifiability of this statement relies on the fact that it is conceivable to measure how easy is the access to the imposed currents (e.g., a measurable property such as flow resistance). The observations will then quantitatively show greater access in time, or not. If not, H2 is false thus making H2 *falsifiable*. Hence CL is *falsifiable*. Noteworthy is that the possibility of no design changes is covered by H1.

With the two parts of CL, H1 and H2, being *falsifiable*, by straight logic CL is *falsifiable*. They are *falsifiable* to fulfill the expectations of Popper unconditional followers (*critical reasoning*). The complexity that arises to test both hypotheses is mere consequence that they are in the verge of a new paradigm as Kuhn [18], Kordig [2] and Feyerabend [19] pointed out.

The last argument will be whether CL can be derived from another first principle. So far it has not [7, 15, 21].

And there is another challenge for the skeptic scientific community: to show why, not how, design emerges by any other means other than invoking the CL or a logically equivalent statement.

All the theories built by invoking the CL are subject of their own requirements of *falsifiability*.

4. THE NAME "CONSTRUCTAL"

"Constructal" was a coined in 1996. A theory's name carries its own meaning. The very first phenomenon addressed by CT was the occurrence of *dendron* structures. The first tree-shaped network ever predicted, not modeled, was the heat-conducting tree for cooling electronics [1]. By the time CL was being stated, fractals were still novelty and a hot topic. The resemblance of fractals illustrations to natural designs [25] stunned the public and overshadowed theories that sought the physics of the nature forms and structures. It seemed that it was the final word: "nature is fractal".

Indeed fractals are a powerful mathematical resource for many things. Since our earlier studies we knew no one was predicting theoretically any of those forms and drawings. They were all descriptive computational artistic rendering based on empirical observations. Prof. Bejan said those renderings could as well be made by a hand drawing with a paintbrush since they did not embody any physics deductive reasoning [1, 4, 6].

We then found a ten-years old editorial calling for the physics behind fractals in agreement with our impressions [26]. It is worth quoting Kadanoff: "(…) *However, further progress in this field depends upon establishing a more substantial theoretical base in which geometrical form is deduced from the mechanisms that produce it."* The editorial ended with "(…) *Despite the beauty and elegance of the phenomenological observations upon which the field is based, the physics of fractals is, in many ways, a subject waiting to be born.*"

It so happens that Constructal Theory showed fractals alone do not deduce natural forms. One can make fractals resemble natural forms as one pleases, but not deduce those forms. Furthermore CT showed natural forms and structures can and must be fully described in classic Euclidian space. Fractals work from large to small until an arbitrary *inner cut-off* scale in order to be represented in paper or screen, while constructal theories showed that forms and structures could be deduced by physical principles if they are seen in the opposite direction of fractals. Branching was replaced by confluence [1, 6]. CT also predicted there would be a smallest scale where the confluence of diffusive slow flow regime would meet the advective fast flow regime. Tree-shaped structures were fully deduced in a progressively growing direction until an area or volume constraint was met [1, 6]. Parts were put together instead of broken apart (fracture). Bejan's training in Latin came in hand to find the word "construere".

5. CLOSURE

In this brief essay, I reviewed how constructal law and constructal theory fit in the main schools of thoughts of scientific methods. Constructal law and constructal theory formed a new useful and explanatory paradigm. The new paradigm is facing the expected resistance from the *establishment,* which is mostly adept to the positivist approach set by Popper's *critical reasoning* or *fasificationism*. I showed that with little adaptation of the original statement, constructal law and constructal theory meet the strictest contemporary paradigm of the scientific method: constructal law and constructal theory are *falsifiable* and *testable*.

Constructal theory belongs to physics because it aids us to understand the world around us and to make predictions as well. While the constructal theory paradigm goes *confirmed*, it will progressively expands its acceptance. If in any fair test constructal law or constructal theory fails to be observed, the constructal paradigm will not be discarded but amended to explain why in many instances it applies and in others not.

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