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Constructal theory and related science education aspects

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ABSTRACT

The *constructal theory* applies to everything that moves, animated and inanimate; in fact, human beings have flow systems within that are obvious manifestations of *constructal theory* (like the circulatory blood system). The understanding and developing strategies to tackle diseases can benefit from better science education of this *constructal theory* applied to the human species in health, on the physiological, mental, and social components, the use of the cyberspace educational resources including those on *constructal theory* available and all that development can lead us to improvement of science, design of science teachers training with the *constructal pedagogical supervision* theory for sustainable development.

Keywords: constructal, education, health, science, pedagogical, supervision

INTRODUCTION

The *constructal theory* establishes that, for flow systems to survive in time, they must evolve to provide greater access to their currents, generating optimized geometries, often with a tree-shaped structure; from river basins to vascular systems, this principle describes not only physical phenomena but also biological, chemical, cognitive, and social processes (Bejan, 2000, 2022a; Bejan & Lorente, 2006).

We look at the actual human body, after millions of years of evolution, a remarkable biological "machine", in is best when in a homeostatic equilibrium. Looking closely at your hands, you realize there are imprints in your skin where it folds but looking closely you realize there is a tree shape pattern (Bejan, 2020). Under your skin the inevitable observation, the circulatory system in tree shape; also within the organs, the vascularized tissue (Bejan, 2022a; Dai et al., 2006); now looking at the respiratory system within the lungs the same pattern (Bejan, 2000, 2020); in your brain the same shape on its circuitry; and the nervous system (Smith, 2001); the flow of stresses on the human body presents the same tree shape. Within the cell, the DNA (Guyton, 1998; Hutchens, n. d.), I highlight its control function of protein synthesis, cell function, and cell reproduction (Guyton, 1998), the polymeric molecule that has its tree pattern designed into its center.

These examples remind us that the human body is built on tree shapes that work concomitantly for homeostatic equilibrium. Simultaneously, what makes all these systems keep functioning are the imbalances, the driving forces that generate flows of stuff that are being compensated at each moment (Bejan, 2000). Does this mean that one's health can be focused on a single tree shaped pattern? If the *constructal tree shape* is everywhere (Bejan, 2000, 2020), should we favor it in human internal and external (society/environmental) flow system treatment strategies such as kidney calculus, gallstones, systemic vasculitis, cholesterol deposition, pollutant intake, etc., and oppositional strategies for therapies that fight diseases like stopping cancer growth and dissemination (Horta, 2022), stopping the cause of fistulas flows development? Should we invest more in *constructal medicine*? All these subjects are fuel for creativity in Teachers when elaboration their lesson plans and for discussion and debate, as in teacher training has in the classroom.

Recent studies suggest that medical interventions can benefit from *constructal theory*, both for restoring optimal flow patterns in pathological conditions and for interrupting detrimental flows, as in tumor growth (Sauer et al., 2021). Also educational applications of the theory show promise for the development of interdisciplinary competencies and social values, and for the new *constructal pedagogical supervision* theory for sustainable development.

Understanding *constructal theory*, its applications and implications by science teachers, not only helps creativity in teachers practice but also pushes the scientific and technological knowledge further, new laboratory pedagogical experiments design can be done and inventions that could be patented might come to reality (Horta, 2022).

METHODOLOGY

We reviewed literature and looked on the Internet for pedagogical instruments that can be used in science teachers training and in classes, about *constructal theory*, optimizing the relationship between *constructal theory*, health, science for peace, science education, and the *constructal pedagogical supervision* theory for sustainable development.

This work followed a conceptual analysis and integrative literature review approach; we searched and analyzed resources from scientific databases such as *Academia*, *PubMed*, *Scopus*, *Google Scholar*, *ORCID*, and *ResearchGate*, patent search engines as well, as core publications and videos authored by Bejan (2000, 2008, 2009, 2010, 2012, 2016, 2020, 2022a, 2022b, 2023), Bejan and Lorente (2006, 2010, 2012), Bejan and Marden (2006), Bejan et al. (2019), and Dai et al. (2006), including in the *YouTube* and on *TED*^{x} websites.

The inclusion criteria where: studies discussing the physical and mathematical foundations of *constructal theory*; biomedical applications, like in physiology, pathophysiology, and oncology; cognitive and social processes associated with the flow and diffusion of information; educational frameworks incorporating *constructal principles*; *constructal industrial property*; *constructal pedagogical supervision* theory for sustainable development.

Results were categorized into medical, cognitive/social, and educational applications. However those medical and cognitive/social results are also subjects for science education exploits. Classic references and recent works from the last 25 years were included to ensure theoretical depth and contemporary relevance.

RESULTS

Principles and Scope of *Constructal Theory*

The *constructal law* was formulated by Professor Adrian Bejan (1996), and it states: “For a finite-size open system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it”. This theory applies to all flows, like flows of mass, fluids, electricity, heat, animals and machines, knowledge dissemination, transport and economic structure, molecular structures, and energy (Bejan, 1996, 2020). According to this theory, natural and engineered systems obey the same principle; shapes evolve as a result of the objectives, maximizing flow access and the constraints (Bejan, 2020). The flow patterns are seen in lots of different contexts like river basins, lightning, vascular networks, rail and road systems, botanical trees, dendritic crystals, molecules with ramified structure, and social organizations (Bejan, 2000, 2020). The *constructal theory* recognizes evolution in both biological and technological contexts (Bejan, 2020; Bejan et al., 2019), where configurations evolve toward better flow efficiency, including in domains where animate and inanimate elements merge, like in biomaterials, artificial cells, particle-based therapies.

Biological and Medical Applications

Looking at flow obstruction diseases, like the kidney stones, atherosclerosis, vasculitis, and cholesterol deposition, they can be interpreted as disruptions in the optimized flow structures, suggesting therapeutic strategies aimed at reestablishing them. Bejan et al. (2019) model solid tumors as adaptive *constructal systems* that reorganize to maximize nutrient inflow and waste outflow (Sauer et al., 2021). This thermodynamic perspective contrasts with purely histopathological approaches and opens novel intervention strategies.

About biomedical engineering developments, the theory has applications in the design of artificial organs, biomaterials, and advanced therapies such as Hadrontherapy (Bejan & Lorente, 2006; Horta, 2022). The drug delivery systems optimization, it can be designed following *constructal principles*, supporting optimal distribution and transport aligned with physiological flows, enhancing their effectiveness in targeted and localized therapies. With the *constructal medicine*, by applying the *constructal law* of flow optimization principles we can understand and enhance biological transport and delivery pathways.

In nature, the flows, like bodies of mass, fluids (Newtonian and non-Newtonian), electricity (Smith, 2001), animal and machine species, knowledge, and energy, all originate the arborescent structures (Bejan, 2000, 2020). *Constructal law* (Bejan, 2000) was first formulated by Bejan in 1996 and refers to flows, evolving over time, meaning that they change; and applies to all inanimate flow systems and to all animate flow systems. Shape and structure are the result of objectives and constraints, with optimization, in nature, and in the artificial, with flows, with internal imbalances (Bejan, 2000). Tree shapes, although usual, do not always have exactly the same draw, whether rivers, circulatory systems, lightning, road and rail networks, botanical trees, dendritic crystals, or social organization (Bejan, 2020; Bejan & Lorente, 2006). A succession of constructs, in the direction of better, creating progressively better shapes, within the objective and constraints (Bejan, 2000), according to Darwin’s observations, also applied to the evolution of machines; this is particularly relevant when more are the situations where animate and inanimate fuse, such as biomaterials (Chang, 2007) like dental, artificial blood, artificial organs, artificial bones and the effective use of sub-particles in therapies such as in hadrontherapy. Over time, mechanical, thermal, fluid, convective, rhythmic, economic shapes and structures, and flows of ideas (Horta, 2022), are generated (Bejan & Lorente, 2006), all of which can be optimized according to this theory, with ever greater access and ease in the passage of the flow and capacity to change in the best direction; over time, imperfections and friction minimization (Bejan, 2020).

Constructal theory has implications in male and female physiologies, movements, and approaches made in sports to optimize the performance of swimming athletes, such as optimizing the spacing between the fingers and toes and swimming harder and faster; it also accounts for all types of animal locomotion (Bejan, 2010, 2020; Bejan et al., 2019). It also highlights the optimization

of running, swimming, and flying, using data collected from resulting forces, velocities, and frequencies with the *constructal law* approach, the optimal distribution of imperfection, how they evolve with the purpose of minimizing the destroyed exergy, and how all forms of locomotion can be described by this single law of physics, showing that metabolic rate is proportional to $M^{3/4}$ (M=body mass), the frequencies of heartbeat and breathing is proportional to $M^{-1/4}$, speed is proportional to $M^{1/6}$, frequencies of flapping are proportional to $M^{-1/6}$, life span is proportional to $M^{1/4}$ and more (Bejan, 2020; Bejan & Lorente, 2006). An analysis was also made of the evolution of the height and weight of the fastest swimming and running athletes, according to this *constructal approach* (Bejan & Lorente, 2006; Bejan & Marden, 2006). There is an analysis made of the hierarchy of mass movements on Earth, of inanimate masses and of animated or living masses, by the *constructal law*, in order to facilitate their access to areas, whether by vehicles, animals, or rivers of water, the pattern of many low-mass bodies and few large-mass bodies, fuel vehicles travel farther, many low-mass bodies are needed to cover greater areas (Bejan, 2016, 2020; Bejan & Lorente, 2006; Horta, 2022). The study of movements either by engineering or living beings based on the wheel is attributed to evolution by *constructal law*, such as the shape and size of organs in living beings, the flow of stresses in bones, legs, skeletons, or the roots of plants (Bejan, 2010; Bejan & Lorente, 2006; Horta, 2022). The shape of living beings is revised by *constructal law*, both at the level of macroscopic flow (Bejan, 2000, 2010, 2020) and DNA (Guyton, 1998; Hutchens, n. d.). The allometric laws observed in human being (Bejan, 2000, 2020; Bejan & Lorente, 2006) and predicted by *constructal theory*.

The *constructal theory* to understand the architecture of the human lungs (Bejan, 2020). It explains that the bronchial tree has 23 levels of bifurcation. This specific structure minimizes resistance and optimizes both the adequate level of oxygen to the alveoli and the removal of carbon dioxide. Using mathematical models, the study deduces the dimensions of the alveolar sac, the total length of the airways and the total resistance to oxygen transport, comparing them with observed physiological data.

The *constructal law* was applied to understand tumor growth by examining it as a flow system that organizes itself to improve access to nutrients and waste removal pathways, similar to other natural systems like rivers, trees, and vascular networks; in the research with Sauer et al. (2021), tumor growth is modeled as a thermodynamic process in which cancer cells and their extracellular environment change shape and structure to maximize access to flow, promoting tumor growth and proliferation. This approach diverges from traditional biological models, which focus instead on the physical and structural organization of tumors. The researchers have developed a predictive theory of tumor growth that approaches the subject from a new perspective.

Cognitive and Social Applications

Regarding the neural architecture**,** the brain connectivity follows efficiency and economy principles, consistent with the *constructal theory* (Bejan, 2000). *Constructal theory* has implications in the human mind and social dynamics**,** related to cognition (Bejan, 2008, 2023; Horta, 2022; Staddon et al., 2007), we highlight the approach of information and knowledge, the evolution of signs and their meanings; the complexity, organization, and design; also noteworthy is the approach to neuronal anatomy, and intelligence in the light of the *constructal law*, the order of cognitive systems according to the principles of efficiency (Bejan, 2009, 2012; Smith, 2001); another interesting approach is the relationship between vision, the golden number, the locomotion of living beings by *constructal law* (Bejan, 2009, 2021); cognition as a *constructal phenomenon* where thinking, knowledge, thinking again and better and further on, the *constructal evolution* of the brain (Smith, 2001). According to the *constructal theory* author in an episode of the much-appreciated TV series “Through the wormhole” with Morgan Freeman, with the basketball game (as a *constructal sport*), a parallel can be made with what an individual is trying to do in life (in social dynamics), there are those who are trying to open new channels of flow while others are trying to block them.

About the diffusion of good ideas where *constructal empirical studies* show “S-shaped” adoption curves (Bejan, 2020), which can contribute to educational and communicational strategies for promoting health and peace (Horta, 2022). Still the example of the physics of the dissemination of ideas, the propagation of ideas generated by research with the *S*-shape, two phenomena are highlighted, the first, long and fast, and the second short and slow (Bejan & Laurent, 2012), and its potential application in education, of generators of peaceful ideas to the young people who will receive and internalize these new ideas (Bejan, 2009, 2010; Horta, 2022). Openness to ideas for inventing medical products is usually announced by many companies as in open innovation platforms like Wazoku and Hero^{X}, as in the company’s own websites; so are there many medical inventions from citizens scientists based on *constructal theory* or from research empires (Bejan, 2008; Bejan & Lorente, 2010)? Should medical doctors be motivated and/or trained to patent a new good idea/insight that they might get from their professional experience and knowledge?

About peace and humanity, historical cases, such as Portuguese diplomat Aristides de Sousa Mendes enabling the escape of Jewish refugees during World War II, reflect the principle of unlocking vital flows. At the time, Aristides de Sousa Mendes and other Portuguese diplomats disregarding orders, unlocked flows by giving visas to persecuted Jewish people by the Nazis saving then many lives; today we must unlock efficiently flows of food to babies of the poorest, worldwide, there are studies that to many start school with less brain mass due to lack of adequate nutrition on early age (Hair et al., 2015).

Educational Applications and Science Teachers Training

Constructal theory concepts can be embedded into science curricula through modeling biological, physical, chemical and social flow systems; in Teacher education, both preservice and in-service science teacher training can incorporate *constructal principles* to foster systemic reasoning. Many practical activities can be developed, like with phylogenetic tree using cytochrome c sequences tree analysis, flow modeling, and interdisciplinary problem-solving exercises, and discuss it with his students, using *constructal theory* (Horta, 2022).

Many more science for peace conceptual examples to deliver in science teachers training and in school science classes can be created, following published ideas like the science professor can contextualize to his students that the pressure inside the anterior chamber of the eye, called intraocular pressure, can be analyzed in relation to the biomechanical properties of the corneas, using

the *constructal law* (Lucia et al., 2016). Analyzing intraocular pressure, which is the pressure of the fluid inside the eye, the progressive loss of vision related to any disturbance of intraocular pressure is known as glaucoma and represents one of the main causes of blindness. Furthermore, intraocular pressure measurements are one of the most important medical parameters in the postoperative evaluation of corneal, lenticular and vitreoretinal diseases.

In class the Teacher can exploit pedagogically *constructal patents* (Horta, 2018, 2019), creating opportunities for new science for peace educational contexts, approaches, school laboratory experiments. The application of the new *constructal pedagogical supervision* theory for sustainable development provides great opportunities for the educational system quality (Horta, 2022).

Since the author of the *constructal theory* is a scientist who keeps working, there is a wide range of curated resources in cyberspace with his pedagogical and scientific intervention, where various pieces of information about this theory are gathered (some of the most important developments in the field). Examples are playlists on YouTube, an example "Adrian Bejan–*Constructal law*" (Bejan, 2022a) containing 25 videos like "Freedom and evolution", "Lectures during lockdown", "Predicting evolution", "Science of inequality and injustice", "Pictures don't lie", "Why the bigger are more efficient", "Night of ideas", "Solar powering space", and "Discipline in science , from thermodynamics" among others.

Doing a search in the TED platform, we find several videos where the authors give presentations and lectures. Bejan has participated in TED^{x} Talks, such as TED^{x}Bucharest and TED^{x}MidAtlantic. In the Duke University website we also find today lectures by Bejan that were recorded on video. The recorded moments are in different places and moments and present valuable knowledge about the construction theory, design or configuration of the evolution of animate and inanimate things. There is a Constructal Blog (2017), and it is a blog dedicated to *constructal theory* and its applications in various areas of knowledge and serves as a space for discussing ideas and exploring how *constructal theory* can be applied in various areas such as physics, biology, economics, engineering, architecture, among others. The blog contains texts explaining the theory, detailing how it can be applied to understand and optimize different systems. This includes studies on fluid dynamics, energy systems, transportation networks, and biology, among others. The blog also reports on events, conferences, and relevant publications on *constructal theory*, bringing together experts and enthusiasts on the subject. There are practical applications and everyday examples: in several posts, the blog presents examples of how *constructal theory* can be observed in everyday phenomena and how it influences projects and technological innovations.

All this flows of good ideas can be used in the design of science teachers training with the *constructal pedagogical supervision* theory for sustainable development (Horta, 2022).

DISCUSSION

Findings indicate that the *constructal theory* serves as a unifying paradigm connecting physical, biological, chemical and social patterns through the principle of optimized access to flows. In medicine, the approach emphasizes the structural and functional integrity of flow networks rather than isolated structural alterations, offering a complementary path to traditional diagnostics and treatments.

In education, *constructal-based strategies* encourage interdisciplinary integration, critical thinking, and creativity. These can enhance not only scientific literacy but also social responsibility, industrial property and peace education.

Using industrial property new pedagogical school laboratory experiments can be implemented by the science teacher, where can promote in the school science laboratory the construction of *constructal prototypes*, do with students the patent analysis to identify and understand where the subjects taught in their discipline are.

Limitations of the present analysis include the theoretical nature of most existing applications and the need for empirical validation, especially in biomedical contexts. The design of continuous science teacher training on applied *constructal theory* and also in initial science teacher training (in universities and in polytechnics) can be an advantage that we should not put aside; also in health, on the physical, mental, and social components, and all that development can lead us to the rise of *constructal medicine*.

The *constructal pedagogical supervision* theory for sustainable development optimizes "flows" of knowledge in the classroom, aligning teacher training design with natural learning patterns and expanding conceptual creativity

Future directions include the development of predictive computational models for chemical and biological flow systems; assessment of *constructal-based educational programs*; translational research bridging physical flow theory and clinical practice; development of *constructal-based diagnostics* and *constructal-based therapies*; using the *constructal pedagogical supervision* theory (Horta, 2022) and doing the determination of the Higgs indexes, the Horta indexes and the Bejan indexes from teacher training centers and publish the rankings from consecutive years to understand their evolution and can look for relations with other indexes like the human development index or the unemployment index, from a city, a region or the country.

CONCLUSIONS

Constructal theory presents significant potential as both a conceptual framework and a practical tool in medicine, science for peace and science education. Its application can lead to more effective therapies, integrative teaching methodologies, and innovative solutions for flow-related challenges in natural and social systems. Interdisciplinary and empirical studies are recommended to consolidate their theoretical and practical contributions. *Constructal theory* shows us the biophysics, also that *constructal physics* applies from the smallest particles behavior within till the human body size with the concomitant tree shape

flow systems within, the evolution of animate and inanimate that are likely to blend (like with artificial cells, artificial blood, artificial organs, biomaterials, etc.), and social dynamics, creating opportunities for new educational contexts and approaches, we should learn, as in initial science teachers training as in continuous education designed with the *constructal pedagogical supervision* theory for sustainable development, to apply the discoveries made, improve as in science teachers as in their students, knowledge on science for peace, health and *constructal medicine*, providing fuel for creativity and innovation in science education and for peace. More studies can be plentiful, looking for more related science education aspects with *constructal theory*, in and out of cyberspace and for other pedagogical resources.

Constructal knowledge dissemination benefits from online video lectures, TEDx presentations, blogs, academic websites, and open innovation platforms. This digital presence extends the theory's application in both formal curricula and public engagement. Including *constructal theory* in science teacher training (both in the initial stage and in the continuous) equips educators to foster systems thinking, sustainability, and peace oriented learning. A proposed *constructal pedagogical supervision* optimizes "flows" of knowledge in the classroom, aligning instructional design with natural learning patterns and expanding conceptual creativity.

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