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Hydrology and Earth System Sciences Discussions

Interactive comment on "Constructal theory of pattern formation" *by* A. Bejan

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Response to Referee #1

This journal should publish the names of its discussers in the same way that it publishes the names of its authors.

I thank the referee for his comments, but I plead not guilty to his accusations. I see no place for his tone: I think he wishes that he had formulated the constructal law first. I respond in order to his list:

1. The claim that I do not reference Rodriguez-Iturbe and others is absurd. From my first constructal articles and books (Bejan, 1997d), I have referenced not only Rodriguez-Iturbe but also Rinaldo, Banavar, Malkus and many, many others much older and more famous who had similar "hunches" (Heron of Alexandria, Fermat, Maupertuis, Leibnitz). In my first book on constructal theory I even reproduced (!) a figure from

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Rodriguez-Iturbe's book: see Fig. 6.3 in Bejan (2000).

Look, my article was a brief review, which I gave as an invited one-hour lecture at a very interesting and lively conference. I listed plenty of references to guide the audience where to find the rest of the story. I should not be expected to repeat in a few pages the entirety of my point of view (e.g. the above names), to which I dedicated several books.

I cited Rodriguez-Iturbe's book and articles in my first disclosure of constructal theory not because his book (1997) influenced my accidental work (1995) (how could it?) [I was unaware of him in Texas *and* fractal geometry], but because I have an interest in history, in how ideas flow (evolve, improve) to become and persist as our science and civilization. See Sect. 13.9 on "Science and civilization on constructal flow structures" in Bejan (2006).

I discovered his 1997 book in the course of writing my second book (2000). I was very pleased to see similarities; I commented on the similarities and the differences. I continue to cite Rodriguez-Iturbe in my articles. He and I are contemporaries, not leader and follower.

While it is true that Rodriguez-Iturbe is one in a series of authors who invoked *ad-hoc* a principle of *minimization* of dissipation, this is not true of Bejan and the constructal law. Read again Sect. 1 of my article. The constructal law is not about "dissipation", or "optimization", and certainly not about Rodriguez-Iturbe's "fractal river basins". Far from it, in fact, in Bejan (1997d, 2000) I demonstrated (with a coffee grounds experiment) that "fractal river basins" do not exist.

To repeat the start of my article, constructal theory begins with (1) the statement that the generation of flow configuration in time is a *physics* phenomenon (a behavior of anything, anywhere, if that flowing thing is free to morph). (2) spells out the constructal law, which identifies the time direction of the sequence of configurations (drawings)—the direction of greater and greater access for the currents that flow through the

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nonequilibrium thermodynamics system, and (3) makes the claim that (2) is a law of all physics.

Regarding Dewar (2003, 2005), the constructal law (1996) preceded his work by seven years; therefore he is the one who should have acknowledged the precedent, not I. I was unaware of Dewar before the Perth 2005 conference that generated this special issue. I see that even in his 2005 paper Dewar continues to not acknowledge the constructal law, in spite of the fact that in 2003 constructal theory was the cover story of the largest-circulation science magazine in his country and language (France; see my reference Poirier, 2003). He is the one who is misleading his readers, not I.

But, how can this reviewer blame me for Dewar and Rodriguez-Iturbe at the same time? Dewar preaches *maximization* of dissipation, and Rodriguez-Iturbe *minimization* of dissipation. Together they represent the Tower of Babel if not cacophony. It was constructal theory that showed that these seemingly antagonistic *ad-hoc* statements are consistent with a single statement: the constructal law (Reis and Bejan, 2006).

The claim that Dewar's "derivation" is more "fundamental" is wrong. (it is not even a new *ad-hoc* idea, see Paltridge). I guess the reviewer thinks this because Dewar's is from statistical physics, and Bejan's is from highschool physics. The reviewer's claim is equivalent to saying that Botzmann's statistical argument is more fundamental than Carnot's principle and the laws of classical thermodynamics. Nonsense.

If Dewar's "derivation" is something new, then what he derived from existing laws is not a new law. This difference alone places Dewar's claim in a different (lower) category than the constructal law. The constructal law is a law because it is not derivable from other laws of physics.

Idea A is "more fundamental" than idea B when the area covered by A is larger (a bigger base, literally a "bottom" in Latin) than the area covered by B. I did not see *any* drawings or temporal patterns predicted by Dewar. How can such *opacity* be more fundamental than, say, Rodriguez-Iturbe's *ad-hoc* minimum dissipation, or Bejan's constructal law?

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2. The referee's example with the half-circle channel cross-section is not original. I said it first, in this article and in my first book (Bejan, 1997d). I noted that river cross-sections with vertical river banks cannot exist, because of erosion under gravity and water friction, and that the natural river cross-sections will result in being shallower, more like the shape of a watermelon slice.

The width-depth proportionality that I deduced from the constructal law corresponds to the simplest (naked, stripped down) setting. In this extreme, the law demands that the width/depth ratio must be a constant greater than 1.

It is very likely, and this can be done in second-generation papers, that if one adds gravity, water friction, soil mechanics and erosion to the problem formulation, one will predict other width/depth ratios. But, success on this route should not blind us: the *existence* of the proportionality is proclaimed (demanded) by the constructal law, not by the more realistic features included in the problem formulation.

The referee's comment is completely analogous to the claim that, when dropped from the Tower of Pisa, neither the pebble nor the feather obeys Galilei's law of gravitational fall. The claim is correct, but it does not invalidate Galilei's law. The reason is that Galilei stated his law in the simplest (naked, stripped down) setting.

About why the constructal law is a law: we see examples of flow configurations that come in the billions, billions of trees (rivers, lungs, snowflakes), billions of cross-sections (blood vessels, river cross-sections), billions of droplets that impact walls (splat vs splash), billions of reproducible transitions to turbulence, etc., etc. I think that "coincidences" that are so overwhelming in numbers are manifestations of a principle, of a tendency in nature. First I identified the physics phenomenon that brings together all these billions (the generation of flow configuration in time), and then I saw the principle (the constructal law). I still have not found an example that contradicts this universal tendency of nature.

3. The part (Sect. 7) that displeased the referee are the notes that I wrote in my bench

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during the concluding session of the 2005 Perth conference. They represent my impression at the end of a week of hydrology research—my first hydrology conference. I was struck by the similarities between the challenges in hydrology research (data collection, measurement techniques, instrumentation, modeling, simulation, money, money, money) and challenges in other hot fields such as turbulence and animal design.

It occurred to me that smart people who work so hard should consider the possibility that the reason why they have to measure (i.e., why they cannot predict, after centuries of trying) may be due to the fact that the list of principles they recognize is incomplete. It also occurred to me that in fields where the *ad-hoc* invocation of a hunch is successful over and over again, should give these hard working people the courage to call the predictive hunch a law of physics. None of the names mentioned by the referee called their hunches a law of all physics. With the constructal law, I did just that—I did it before I knew much about hydrology, turbulence, animal design, etc. (in other other words, I did it *because* I was not weighted down by knowing too much).

Ignorance is an asset to the creative mind, because it allows it to move and morph freely. Freedom is good for design, including science (see Sec. 13.10 I my latest book, Bejan, 2006).

Finally, comments 10 and 17 made by referee no. 5 are excellent and very sharp comments on Rodriguez-Iturbe and the position taken by referee no. 1.

Response to referee no. 4

I thank the referee for thinking and writing about my work. In response, I draw attention to my reply to referee no. 1, because in that reply I covered most of the points raised by referee no. 4. Here I respond only to the new elements signaled by referee no. 4.

I have no idea why the referee sees “optimality-based theory” in the constructal law. Read again Sect. 1 of my paper. The constructal law is about a time direction in nature:

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the time direction of an “animated movie” in which existing flow configurations are replaced by configurations that flow more easily. Nothing more, and nothing less. There is no claim that the natural configuration is the optimal, the best, the perfect, or that it is destined to become such. On the contrary, I wrote that no configuration is destined to be a particular configuration. The constructal law is about an undeniable tendency in physics, which is that if given time and freedom to morph, flow configurations will change in one direction: to flow more easily.

I gave references (some, thick books) so that the reader who wants to judge the predictive record of the constructal law can in fact judge it. This reviewer did not do that. His literature search is what he already knows (e.g. optimality “theories”).

He writes that “I want my theory to be regarded as being independent from earlier extremal theories”. Hardly. The constructal law is naked, on the table. The truth is that I want to be known for what I said, and when I said it. Any author wants that.

True is also that the constructal law is different than the optimal/extremal things that the referee knows. It is also true that when I saw the constructal law as a law of physics (by accident in 1995, first papers in 1996) I was unaware of the optimality/geophysics work that the referee mentions. As soon as I discovered the connection with earlier *ad-hoc* hunches in geophysics, I drew attention to how *unifying* the constructal law is (e.g., Bejan 1997d, 2000).

I did not propose the “third law of physics”. I have no idea how many laws there are in physics, and in what order.

I did claim that the constructal law is a law of physics, a law of every thermodynamic system that is not in equilibrium, a law of all flow systems in geo, bio, engineered, social organization, etc. All flow systems have configuration, and they obey the constructal law.

I view the constructal law as a new law in thermodynamics, because it covers an im-

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portant aspect of nonequilibrium thermodynamic system behavior that the first law and the second law do not cover: if given time and freedom to morph, such a system acquires *configuration*. This is a huge deal, it is the law of design in nature. Current thermodynamics is about systems as black boxes, without configuration. Nature is not like that, in fact, without configuration (pattern, design) for us to discern, there would be no science, no language, no civilized man, non "vision" in animal design, etc.

It is OK to be scared by the application of the constructal law in biological design, not just in inanimate systems. We all come from the same dogma: as the referee wrote, we are taught to believe that there are "huge differences between physical and biological processes". Earlier generations were taught by the church that there are huge differences between man and animals. Now we know that all these flowing things obey the laws of physics, because after all physics means everything.

A new idea should be judged on its power to *predict* new observations, and to *condense* huge volumes of empirical information. The constructal law has demonstrated this power, and continues to demonstrate it (new constructal papers are published every month by more and more groups). How could this reviewer come to the conclusion that "the constructal law cannot deduce actual patterns"? This makes no sense.

The reviewer does not like the constructal law because it is "too general" (I guess, he means too general relative to the *ad-hoc* ideas of the optimality/extremal work). His comment is precisely why the constructal law is a law, and why all the other *ad-hoc* invocations of min/max dissipation principles are not laws. I disagree with the reviewer, because I prefer the most general statements, and because science needs both, the many (empirical data, hunches, models) and the singular (the laws). See Sect. 13.9 in Bejan (2006), on science and civilization as constructal flow structures.

The referee writes that in all the examples that I showed [correction: I *deduced* these configurations, I did not "show" them] "it is believed that physical processes occur at local scale and the pattern emerged at the greater scale". Wow, "it is believed" by

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whom? And based on what law?

The referee's position is the dogma that all things in physics can be deduced if we dig deeper and deeper into the infinitesimal, the local, the particle, etc. He may be right, but one hundred years of failure suggests otherwise. Furthermore, Galilei, Newton and Sadi Carnot did not have to wait for this "infinitesimal" crowd behavior in order to say big things in extremely compact form. The last line in my 2000 book *Shape and Structure, from Engineering to Nature* explains that the constructal law goes against the infinitesimal belief. I wrote "this book is a jolt the other way, a means to rationalize macroscopic features, objective and behavior".

In the drainage basin problem, we used Darcy flow for the wet banks and the channels (higher permeability for the channels) in order to simplify the numerical simulations, and to show this "movie" sequence of easier and easier flowing configurations. I did indicate (as the reviewer notes) that Darcy flow in the channel is conceptually valid as an approximation of laminar channel flow. The big thing is that even in this simple numerical set up, if one invokes the constructal law at every point in time, one discovers a tree-shaped flow architecture on a piece of paper where in the beginning there was no drawing. Such is nature, and the constructal law captures it.

Response to referee no. 6

I explained what "easier access" means: see paragraphs 5-7 in Sect. 1, where I juxtaposed the constructal law to the second law. I asked the reader to consider an isolated system (nothing interacts with it), which is initially not in equilibrium. In time, the second law says, the system will evolve toward equilibrium (nothing moves, death). In time, the constructal law says, *currents* will flow in *configurations* that provide easier access to them. In other words, because of the natural tendency captured by the constructal law, the isolated system will march toward equilibrium (death) faster if it is free to morph and to acquire flow configuration (faster than if it were not free to morph).

I am not at all familiar with the "counter example" of the out gassing of CO_2. I will take

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a look, but this example is not a contraction at all. Furthermore, I wrote about it. The water current configuration is a lot bigger than the river channel: the job of this current is to find configurations that give it more access to where it came from, namely *the atmosphere* (it came down as rain and it gets back up there as evaporation). So, the river channel is just one portion (one resistance) in the return path, which concludes with evaporation from the surface of large stagnant pools (sea, ocean, or these "pools" separated by dams).

Here is how I wrote about the referee's example: "Plants (vegetation) are completely analogous to snowflakes. They occur and survive because they facilitate "rapid" ground-air mass transfer" (Bejan, 2006, p. 770).

The referee thinks that blood vessels are round because they contain fluids under pressure (if that were true they would be spheres not cylinders), but his reasoning it negated by the veins (round but not at high pressure), earthworms and moles at atmospheric pressure in their galleries, the penis in the vaginal duct at atmospheric pressure, etc. These are *flow architectures*, not pressure vessels!, and their configurations (self-lubricating geometries) speak loudly in support of the natural tendency encapsulated in the constructal law.

The referee's objection to my drifting floating object is dealt with in chapter 6 of my 2000 book *Shape and Structure, from Engineering to Nature*. The referee uses the constructal law without realizing it. Force balances (which he mentions) are not enough to carry out this argument. He also invokes "stability", which means that he gives his mind the freedom to assume that he can disturb (arbitrarily) a given configuration (one that satisfies steady state Navier Stokes), and then to *select* from the infinity of ensuing time-dependent configurations the configuration that does this or that. There is no law of physics (like F = ma, or Navier-Stokes) that empowers the referee to do this. But he does it, because it works. Hydrodynamic stability thinking has worked for almost 150 years. All that success now lines up in support of the constructal law. By the way, this observation on the *ad-hoc* in hydrodynamic stability "theory" was my first step in the

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direction of predicting the necessity of the turbulent eddy.

The referee's example with planting a sail at one end the floating object does not change the law. The referee changed the floating object by giving it a new geometry. Fine. The atmosphere and the ocean will grab this object and orient it and push it in such a way that the air and the water rub each other the hardest.

The referee should first study how I used Eq. (5) in order to calculate the numbers listed in the right column of Fig. 3. I got them by converting each traditional group (Re, Ra, etc.) into its equivalent local Reynolds number (to do this, one needs to know the scale analysis of each flow, e.g. Bejan 2004). In Table 3, constructal theory works from right to left: because I know that Re_l must be of order 10^2, I also know all the other transition numbers (Re, Ra, etc.). They all mean a single thing, $\mathrm{Re}_l \sim 10^2$, which is the constructal law.

In his last paragraph, the referee uses again "instability" without realizing its lack of status in physics. See what I wrote about the floating object. Furthermore, one cannot possibly "predict the onset of turbulence" by assuming the existence of turbulence (the "disturbance"). One cannot predict the image that one first observes and then postulates that it exists. This is why a theory of turbulence did not emerge before constructal theory. The challenge was to predict the configuration that is initially completely unknown (alien, absent).

Some of what I wrote in response to referees nos. 1 and 4 also holds for referee no. 6. The three referees together illustrate why my Section 7 is essential. The referees are comfortable with the state of intellectual debate in their field, and think that past authors and ideas have covered all the physics that was to be covered.

To them the constructal law is a threat. This I understand, and I take it was a huge compliment. I am an *amateur*, not an expert, but when I see patterns and coincidences in the billions and billions, I hear them calling "predict us!" This I did with the constructal law, and I am very encouraged to see that referees nos. 2, 3 and 5, the Editor and the

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organizers of the Perth conference understood what and why I said it.

Adrian Bejan

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