A. Bejan, Int. J. of Design & Nature and Ecodynamics. Vol. 3, No. 3 (2008) 177–189

CONSTRUCTAL SELF-ORGANIZATION OF RESEARCH: EMPIRE BUILDING VERSUS THE INDIVIDUAL INVESTIGATOR

ADRIAN BEJAN
Department of Mechanical Engineering and Materials Science, Duke University, Durham, NC, USA.

ABSTRACT

"Empire building" is a phenomenon that dominates today's research landscape. Large groups, national priorities and research centers dwarf the spontaneous individual investigators. Administrators and the thirst for higher rankings encourage this trend. Yet, the individuals do not disappear. This paper explains why. It attributes the emergence of the large group to the pursuit of greater visibility for the institution as a whole. The visibility (V) is modeled as a product of the production (P) of ideas in the institution, and the support (S) that the institution secures for the production of ideas. The coalescence of some investigators into a large group tends to increase S and decrease P. On the other hand, an increase in the number of individual investigators has the opposite effect. From this trade-off emerge the main and well-known features of contemporary research organization: the proportionality between the size of the large group and the size of the entire institution, the strong relationship between the visibility of an institution and its size, and the fact that large groups occurred first in the largest and most research-intensive institutions. The paper also shows that as the incentives for large-group research become stronger, smaller and smaller institutions find it beneficial to abandon the individual investigator mode and seek a *balance* between research empires and individual investigators. The individual researcher will not disappear.

Keywords: academic mafias, constructal theory, dark networks, research organization, self-organization.

Science d'où prévoyance,
prévoyance d'où action.

[From knowledge comes foresight,
from foresight comes action.]

Auguste Comte [1]

1 AFTER SPUTNIK

The history of scientific research began with the individual investigator: Archimedes, Galilei, Descartes, Newton, Darwin and so on. Name the field, pick up the most modern treatise, and you see the individuals and their ideas. The better ideas travel far (touching more domains) and have more lasting power.

This pattern of solitary thinkers roaming on the landscape of phenomena, facts and ideas went on forever, unquestioned. It continues today because it is natural: science is good for the mind of the thinker, and for the well-being of the entire society.

Something very different happened after Sputnik, a natural reorganization of the research pattern that deserves scientific scrutiny. Large research groups started to emerge inside institutions that were traditionally homes to individual investigators. This change was triggered by the abrupt definition of national priorities and the substantial increase in funding for fundamental research (i.e., basic science).

Sputnik is only the best-known trigger, because it is recent, and because it caused a cataclysmic change in the research pattern. The phenomenon however has a longer history, all associated with national priorities of one kind or another, for example, radar and atomic bomb development in the

ISSN: 1755-7437 (paper format), ISSN: 1755-7445 (online), http://journals.witpress.com
DOI: 10.2495/D&NE-V3-N3-177-189

USA during World War II, aircraft development in Germany during World War I, military engineering during Napoleon I, etc.

Large groups appeared first in the larger institutions that were already noted for their research activity. The phenomenon spread and continues to spread to smaller institutions, so much so that today group research is the main research pattern. Yet, the individual investigators do not disappear. Why?

In this paper I propose a theoretical framework in which to predict and explain the emergence of the large-group phenomenon in research organization. The basis for this framework is the view that ideas (research, education, news, information) flow and bathe the entire globe, like all the river basins combined. Every living system and sector of society is a conglomerate of mating flows that morph in time in order to flow more easily: fluid, heat, animal bodies, information and so on. It is a view that is gaining ground in biology research – the system (our object of study) and the environment morphing and evolving together [2], the emergence of self-organization and design-like features in colonies and bio flow systems as *balances* between few large and many small [3–6], and the unexpected global pattern (crowd intelligence) that emerges when the members of a large group pursue the same objective while communicating closely neighbor to neighbor [7].

The view that society is a flow system with intertwined morphing (improving) architectures was part of the original disclosure of constructal theory [8–12]. This deterministic physics principle is in sharp contrast to the empirical (descriptive, modeling) approaches that have been tried to explain social organization [13]. The traditional approach is to examine societal patterns in the way that one views the photograph of a turbulent flow. Even though the existence of structure is obvious, the image is so complicated, and so much the result of individual behavior (randomness), that description is the norm, not prediction.

Society may be complicated, but pattern is not. Indeed, pattern is "pattern" because it is not complicated. If it were not simple enough for us to grasp, it would be noise, chaos, turbulence and randomness. Strikingly clear patterns demand theory and principles. Constructal theory made a first step in this direction with a physics prediction of Zipf's law: the multi-scale distribution of city sizes over Europe [14], and the origin and rigidity of the annual rankings of universities [15]. In this paper we see how the theory accounts for the internal structure of the modern research university, and why large clusters (e.g., research centers) must coexist with solitary free thinkers.

2 MODEL

The research institution is represented by the size A, and the partitioning of this size into N_0 elemental research units of size A_0, and one larger unit of size A_1. By "size" we mean all the properties (the magnitudes) that differentiate between a small A_0 and a large A_1, for example, numbers of researchers, floor space, paid salaries, and the cost of pursuing the projects located on A_0 and A_1. For simplicity, we use a single measure of size, namely A_0 for "small" and A_1 for "large." The global size of the institution is fixed:

$$A = A_1 + N_0 A_0, \quad \text{constant.} \tag{1}$$

The same constraint can be written by expressing A and A_1 in terms of the number of A_0-size units, that fit inside A and A_1,

$$N = N_1 + N_0, \quad \text{constant.} \tag{2}$$

where $N = A/A_0$ and $N_1 = A_1/A_0$. Equations (1) and (2) are represented by the two-scale structure shown in Fig. 1.

From the point of view of constructal theory the institution is a flow system *with architecture*, which evolves in time so that its streams flow with progressively greater ease [14, 15]. The visibility (V) of

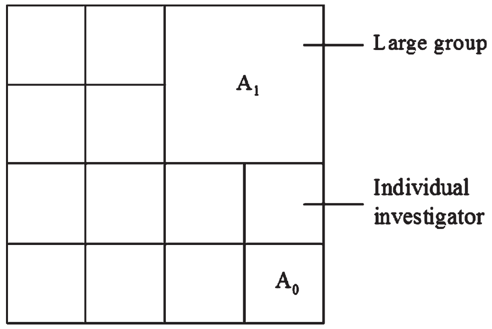

Figure 1: Research institution with internal structure: One large group and many individual investigators.

the research institution is due to the flow of people, goods, money and especially *new information* through the flow system. The empty building that produces nothing is visible, but not from far. The research institution that spends money and does not generate ideas is not visible either. On the other hand, if as little as one good idea emanates from A, then A is known all over the world, and for a long time [15].

In order for a stream of ideas to flow out of an institution, two properties are necessary:

P: Production of good ideas, publishing and "dissemination" (literally, the spreading of seeds) of the creative work, and
S: Support, funding, food, shelter and peace for the special individuals who are creative.

The creative are not workers in a factory, or slaves on a plantation. Their own creativity *defines* the work and the institution. If the work is predefined (prioritized, planned, dictated), as some administrators mold their institutions nowadays, then the work is not "creative," and it is not the subject of this article.

3 SUPPORT

A reasonable assumption is that the support S_i received by the research unit A_i is proportional to the size of the unit. This is true if one thinks of size as being represented by salaries, or by the number of those who work on A_i. The struggle for research grants, however, reveals a bias toward larger grants. During the past two decades in the USA we have seen a shift in the funding culture: government agencies put most of the funds into big projects, research centers and national "priorities." In addition, the number of big-project grant applications is small compared with the number of individual-investigator applications. This shift has the effect of increasing the chances of success of large research proposals focused on "priority" topics.

Loaded with bias is the review process reserved for the big projects. The review is run by the "leaders," the persons who head (or have headed) the big projects. They are the influential, the ones who are consulted during the review process and even before a new research initiative is selected for funding by the government. They are many, not one. They constitute a social stratum known colloquially as academic mafias [16–19] and dark networks [20] (in social dynamics, these terms mean "networks of persons exerting hidden influence"). Favored are the applicants who work for the mafia. Compared with them, the numerous individual-investigator applicants for funding have little chance.

The director and his or her $N_1 - 1$ subordinates attract each other. Here are some of the forces that bring them together:

1. Researchers who think less independently that others find easier paths to promotion by working with (in reality for) the director of A_1.
2. The director needs big-group funding in order to maintain his own visibility, infrastructure and support staff.
3. The publications that the N_1 researchers write as a group are also welcome additions to the list of publications of the director, who is busy as an administrator, not as a hands-on investigator and writer. When the director aspires to the national academy, he points to his list of publications, not to his list of buildings.

Here is why the coalescence into a large entity (A_1) is good globally, i.e., for all the N_1 members. A model for the per-A_i support is

$$S_i = A_i f(A_i), \tag{3}$$

where the bias factor f is a number that increases monotonically with A_i. The total support attracted by the institution (A) is

$$S = S_1 + N_0 S_0 \tag{4}$$

$$= A_1 f(A_1) + N_0 A_0 f(A_0). \tag{5}$$

A reasonable qualitative model for how f increases with A_i is

$$f = 1 + aA_i^{\alpha}, \tag{6}$$

where a and α are positive constants, and the second term accounts on the effect of size on the chances for funding success. The first term accounts for the small-funding limit, where research happens even in the absence of support from external funding agencies. In this limit we have $f = 1$, and Eqn. (5) becomes

$$S = A_1 + N_0 A_0 = A, \quad \text{constant} \tag{7}$$

In this limit there are no forces that would push for a greater or smaller A_1 relative to A_0: the total support S is the same constant for all combinations of one A_1 and many A_0 values on A.

The large-funding limit is represented by the second term in Eqn. (6). By substituting $f = aA_i^{\alpha}$ for $i = 0$ and 1 in Eqn. (5), we obtain

$$S = aA_1^{1+\alpha} + N_0\, aA_0^{1+\alpha}$$

$$= aA_0^{1+\alpha}\,(N_1^{1+\alpha} + N_0). \tag{8}$$

Combined with constraint (2), the large-funding limit shows that support promises to increase monotonically with N_1:

$$\frac{S}{aA_0^{1+\alpha}} = N_1^{1+\alpha} - N_1 + N. \tag{9}$$

Maximum support is achieved when $N_1 = N$, that is when all the researchers work for the large group. This is why many administrators today push for the large group mode at the expense of the individual. They push with internal incentives such as promotion and pay raises.

Why is "total coalescence" not happening in a free research institution? Why are individual researchers tolerated in spite of the attractiveness of the group mode? The answer is that support is one thing and visibility is an entirely different phenomenon [15]. The small fish are in reality not small.

4 IDEAS

Ask what contributes to the idea production, P. Because projects are defined by ideas, every project contributes to P. This means that P is proportional to $(1 + N_0)$, where 1 is the single contribution that defined A_1, and N_0 the contribution of the individual projects thriving on the A_0 values. One may argue that size has some influence on P, and that [by mimicking Eqn. (6)] a more realistic P model would be

$$P = 1 \cdot g(A_1) + N_0 g(A_0), \tag{10}$$

where "1" means that there is only one large group. The size-effect is conveyed by the factor $g > 1$, which increases monotonically with size:

$$g = 1 + bA_i^{\beta}, \quad (b, \beta) > 0. \tag{11}$$

Putting Eqns. (10) and (11) together, we obtain

$$P = 1 + N_0 + bA_0^{\beta}(N_1^{\beta} + N_0). \tag{12}$$

The limit $b = 0$ represents the simplest scenario in which ideas occur: mental viewings occur because of the individual, not because of status, income and title (director vs. subordinate). The last term in Eqn. (12) accounts for the size effect on P, and it is proportional to the expression

$$N_1^{\beta} + N_0 = N_1^{\beta} - N_1 + N. \tag{13}$$

Because N_1 is a number greater than 1, this expression increases with N_1 only if $\beta > 1$, which in the g model of Eqn. (11) would indicate a very strong effect of size on idea production. Such a high β is unlikely, based on the evidence (individual investigators do not vanish). More likely is $\beta \leq 1$, and this means that expression (13) is dominated by increases in N_0, not by increases in N_1. In other words, when N_1 and N_0 are large, the behavior of P is captured most simply by the number of projects, which is the $b = 0$ limit of Eqn. (12),

$$P = 1 + N_0 = 1 + N - N_1. \tag{14}$$

This shows that a larger group N_1 leads to a smaller P. Regimentation is not good for idea production.

5 SUPPORT AND IDEA PRODUCTION

The key finding is that the emergence of the big group (A_1 or N_1) has opposite effects on global support (S) and global idea production (P). This means that there should be a trade off between these two effects with respect to the selection of N_1, but, a trade-off on what basis? Here I offer two arguments in favor of regarding the product $V = SP$ as a measure of the global reach (visibility, influence, power) of the institution A.

The first argument is based on constructal theory. The institution is one point (called A) on the world map (W) of similar institutions with which A collaborates and competes [15]. Ideas (information) flow from point to area ($A - W$), and from area to point ($W - A$). The flow of new information (P) out of the flow system (A) is driven by the support (S). The stream P is analogous to the flow rate of the river basin, while the forcing S is analogous to the elevation (or gravitational potential energy) that drives the river flow. The stream P is the "through" variable, and the driving force S is the "across" variable. The "power" of the flow system is the product of the two, and it generates visibility of magnitude

$$V = SP. \tag{15}$$

All the flow systems of nature have this power structure, the "through" variable times the "across" variable. All flow architectures evolve (morph) in time such that the flow rate increases for a given

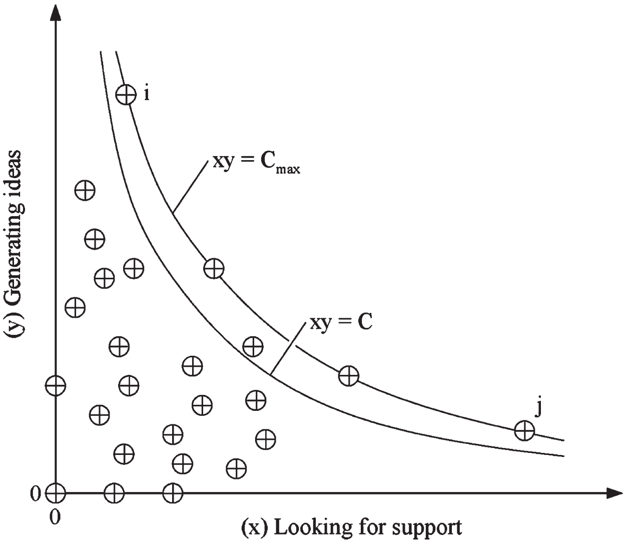

Figure 2: Two objectives in the lives of investigators: (x) Finding support for the research and (y) thinking, writing and disseminating the creative output. They both take time and effort.

forcing. When combined into a product, the evolution points toward flow architectures with greater products. From this general view we draw the conclusion that if A is free to change its configuration, then A will maximize its V in time.

The second argument is anecdotal. Five years ago, I saw a plot similar to Fig. 2 projected on the screen during a meeting of the professors belonging to an engineering department. There was one point (x_i, y_i) plotted for each professor (i), on a field where x_i indicated the professor's annual research funding, and y_i indicated the professor's number of peer-reviewed publications per year. Plotted in this manner, the professors were 24 points that covered an area held between the origin and an apparent equilateral hyperbola, which was not shown (I drew it now, as the curve *i–j* in Fig. 2):

$$xy \sim C_{max}, \quad \text{constant.} \tag{16}$$

Two things struck me about this drawing. First, it was obvious that the points that fell on the C_{max} curve were for the professors whom I was considering "most visible" *before* I saw the graph. Second, professor j identified himself by saying that because his time supply is finite (he is a big-group director), he must choose between looking for research support (x) and publishing (y), and that in a future year, if he "would" trade x for y, his point will slide toward the point of professor i.

I am not so sure. What is clear from Fig. 2 and this discussion is this:

1. For the global visibility of the institution, both are important, the support S and the idea production P.
2. The most visible reside on a curve such as Eqn. (16).
3. Others reside on curves comparable with $xy \sim C$, where $C < C_{max}$.
4. The entire research institution becomes more and more visible when all the C curves migrate away from the origin, matching the C_{max} curve and pushing it out even farther.

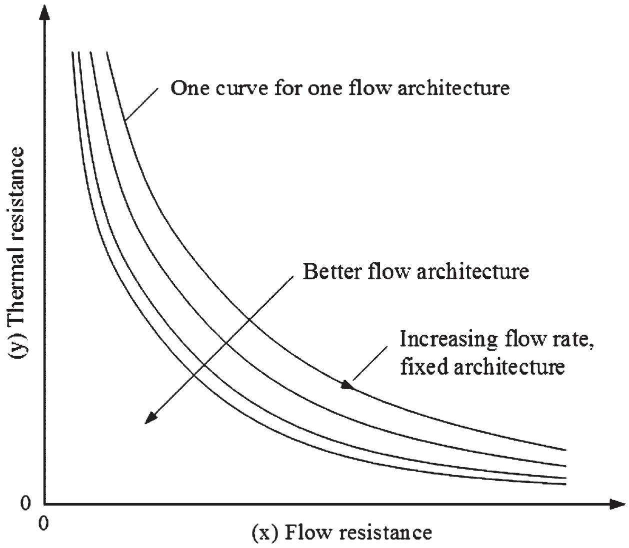

Figure 3: Two objectives in the constructal evolution of architectures for thermo-fluid flow performance (e.g., constructal heat exchangers) [21].

6 VISIBILITY

The pursuit of two objectives at the same time [cf. item (d) above] is in accord with the constructal theory of generation of configurations with multiple objectives [21] (e.g., Fig. 3, in which the time arrow of design evolution points toward designs with small x and small y). The two objectives in a complex thermofluid device are (y) small thermal resistance (intense, compact heat transfer) and (x) small flow resistance. The objectives compete, but both are important. A fixed configuration is represented by a fixed curve. When the device morphs into a better flowing configuration, its curve migrates in the direction of the constructal time arrow, toward small x and small y. This is analogous to the migration of the C curves toward the C_{max} curve in Fig. 2.

This entire argument leads then to a formula of type (15), in which we substitute Eqn. (9) for S, and Eqn. (14) for P. The resulting dimensionless expression for visibility is

$$\tilde{V} = \frac{S}{aA_0^{1+a}} P \tag{17}$$

and depends on the total size (N), the size of the big project (N_1), and the exponent a:

$$\tilde{V} = (N_1^{1+a} - N_1 + N)(1 + N - N_1). \tag{18}$$

The visibility function $\tilde{V}$ can be maximized with respect to N_1 when N and a are fixed. This behavior is illustrated in Fig. 4 for the range $N = 10 - 100$. There is an optimal balance between the size of the large group (N_1) and the number of individual investigators. The optimal size of the large group increases with the size of the institution.

Figure 5 shows that when $a = 2$ the peaks of the $\tilde{V}$ curves are correlated by $N_{1,opt}/N \cong 0.8$ in the entire N range, and that the maximized $\tilde{V}$ scales as N^4. An equilibrium is established between those who join the big group and those who do not.

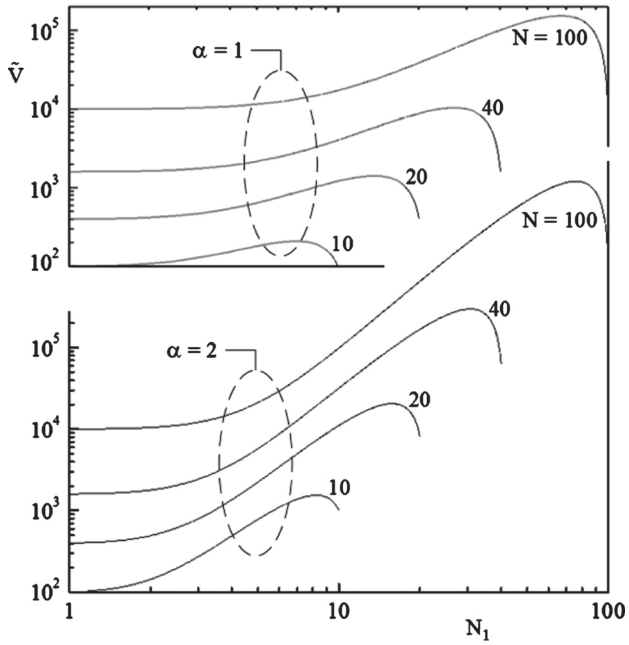

Figure 4: The maximization of visibility through the generation of organization (N_1): A balance is reached between those who join the large group and those who do not join.

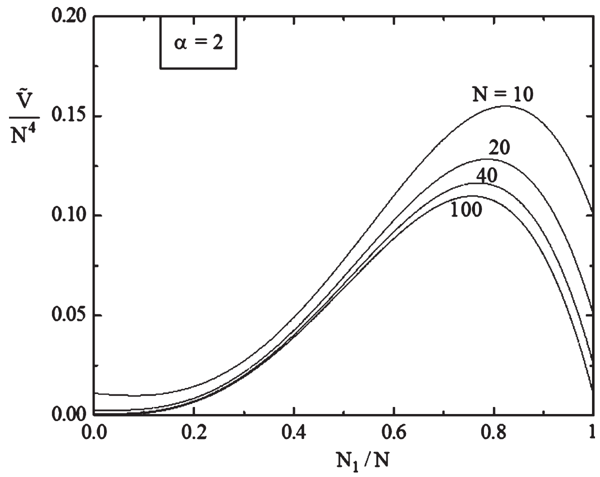

Figure 5: The scaling rules of research institution organization: The equilibrium between the large group (N_1) and the rest ($1 - N_1$), and the rough proportionality between visibility and global size raised to the power 4 (this for $a = 2$).

Table 1: The necessary large-group funding incentive (a) that triggers the emergence of one large group (N_1) inside a research institution of size N.

N	$N_1 = 2$	3	4	5	6
2	1				
3	**0.81**	1			
4	**0.74**	0.77	1		
5	0.70	**0.68**	0.76	1	
6	0.68	**0.63**	0.66	0.76	1

7 EMERGENCE OF THE LARGE GROUP

The simple model constructed so far also captures the phenomenon that large groups tend to occur first inside large institutions. An institution must be larger than a critical size if the coalescence of some of its researchers is to benefit the global visibility of the institution. In other words, if a small institution is to opt for the large-group structure, it will require a large enough a (a critical level of incentives) in order to find this kind of scientific research attractive.

To see this, consider the implications of Eqn. (18) for an institution with just two researchers, $N = 2$. Two designs are possible: (1) no coalescence ($N_1 = 1$), in which case $\tilde{V}_1 = 4$, and (2) complete coalescence ($N_1 = 2$), for which $\tilde{V}_2 = 2^{1+a}$. The large group is good for the institution when $\tilde{V}_2 > \tilde{V}_1$, and this will happen when the large-group funding incentive is significant enough so that $a > 1$.

The next larger institution ($N = 3$) has three possible designs, represented by $N_1 = 1$, 2 and 3, and, respectively $\tilde{V}_1 = 9$, $\tilde{V}_2 = 2^{2+a} - 2$ and $\tilde{V}_3 = 3^{1+a}$. A group of two researchers is beneficial for the institution when $\tilde{V}_2 > \tilde{V}_1$, which happens when $a_2 > 0.81$. Complete coalescence is the better design when $\tilde{V}_3 > \tilde{V}_1$, which means $a_3 > 1$. Because a_2 is smaller than a_3, and because research funding incentives grow in time from low to high (as noted in the post-Sputnik story, Section 1), the emergence of the large group is triggered by the first incentive, which is represented by the smallest a. In conclusion, if funding incentives are strong enough, the institution with three researchers will first develop an organization in which two researchers form a group and the third continues as an independent investigator.

These calculations were continued for progressively larger institutions ($N = 4$, 5, 6), and the results are listed in Table 1. The number indicated in the table for each pair (N, N_1) is the minimum a value required in order for the large group (N_1) to be beneficial to the institution (N). The values in bold indicate the smallest a for a given size (N): this is the lowest incentive that triggers the formation of the first large group. The table shows that the large group is larger when the whole institution is larger.

The construction started in Table 1 was continued in Fig. 6 by plotting the $a(N_1, N)$ curves resulting from requiring that no coalescence ($N_1 = 1$) is outperformed by the emergence of one large group ($N_1 > 1$). Analytically this means using the function $\tilde{V}(a, N_1, N)$ of Eqn. (18), and setting

$$\tilde{V}_1\ (a, 1, N) = \tilde{V}_{N_1}\ (a, N_1, N). \tag{19}$$

Figure 6 is a plot of Eqn. (19), which yields a = function (N, N_1). This figure confirms the trend started in Table 1 and summarized now in Fig. 7. The size of the emerging large group is almost proportional to the size of the institution, $N_{1,\mathrm{opt}} \sim 0.4\ N^{0.93}$.

The lower graph of Fig. 7 illustrates the history of the large-group phenomenon in scientific research. Funding incentives for scientific research come from modest beginnings and have been increasing in time. This means that when a government or national priority establishes a small incentive

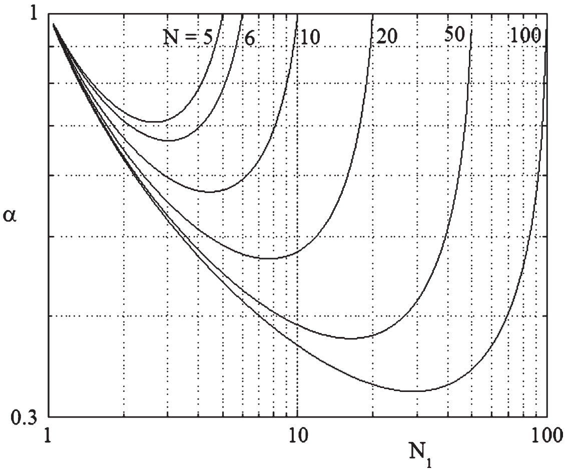

Figure 6: The funding incentive (a) necessary for the emergence of one large group (N_1) among the N researchers of one institution.

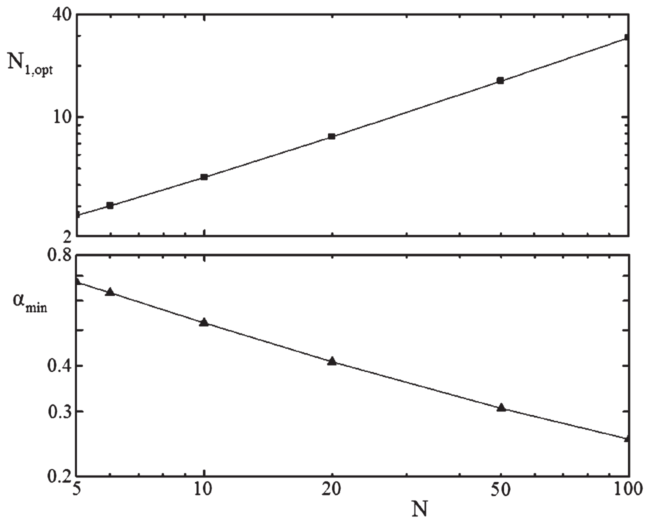

Figure 7: The smallest of the funding incentive (a_{min}) that leads to the emergence of the first large group ($N_{1,opt}$) in a research institution of specified size (N).

(for example a_{min} = 0.3 in Fig. 7), an institution must be larger than a critical size (i.e., larger than N ~ 50 when a_{min} = 0.3) in order to take advantage of the new funding climate. This is why at the time of Sputnik (or World War II earlier) the large-group funding went to the few large institutions on the map at the time (MIT, Caltech, University of California Berkeley, Stanford). Later, when funding increased, more and more of the smaller institutions morphed into structures containing large groups that coexist in equilibrium with individual investigators.

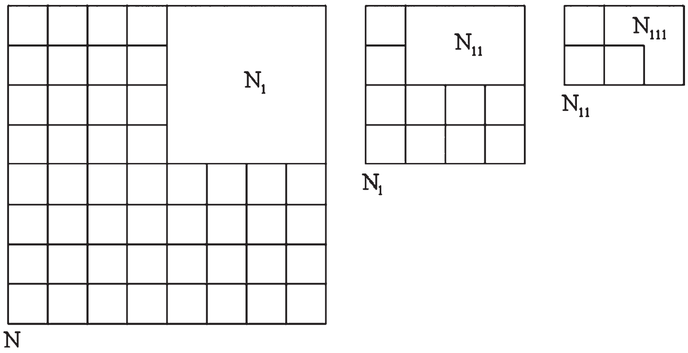

Figure 8: Telescopic structure of self-organization at several scales inside the whole.

8 CONCLUSIONS

The theoretical framework proposed in this paper explains in simple form many of the features of self-organization in contemporary research:

1. The coexistence of research empires with individual investigators.
2. The scaling of the size of the large group with the size of the entire institution.
3. The strong relationship between the size and the visibility of the institution.
4. The emergence of the first large groups in the largest research institutions of the era.
5. In time, as incentives (a) become stronger, small institutions also organize into combinations of large groups and individuals.
6. Complete coalescence into large groups is not happening.

The model that led to these conclusions is admittedly very simple. In fact, it is so simple that it invites objections from both sides, the members of empires and the individuals. The member of the empire may argue that by assigning only one idea to the large group, the calculation of the global P in Eqn. (12) underestimates the idea production that goes on in the large group. This point is legitimate, which is why the present model can be reexamined by using a finite b value ($b < 1$) in Eqn. (12), instead of $b = 0$. The conclusions would be qualitatively the same as those drawn here based on assuming $b = 0$.

Even better, this objection contains hidden support for the simple model. If the larger group produces more than one idea, the additional ideas came from the phenomenon of self-organization proposed in this paper. When the group N_1 receives a large grant, a subgroup N_{11} of the large group remains focused on the single idea that defined the grant application, while the remaining members of the large group ($N_1 - N_{11}$) exploit the new funding in order to increase their own *freedom* to explore new directions. The large group develops internally a two-organ structure of the simple type sketched in Fig. 1 for the whole institution. The forces that led to self organization at the largest scale (A) are also present at the next smaller scale (A_1). And so on, from small to large scales. When sufficiently large, the institution is more complex than in Fig. 1, but its complexity is the result of the balance between large groups and individuals at more than one size scale (see Fig. 8).

From the individual's perspective, the counting of the large-group idea (e.g., one scientific paper) on the same basis as one idea-paper published by an individual investigator is openly unfair. The single paper produced by the group required N_1 paid salaries, not one, i.e., a lot more than one idea-paper produced by one individual. In Fig. 2 then, the *y* value of professor *j* should be divided by the average number of coauthors that appear on *j*'s papers.

Here is why researchers should be interested in the self-organization phenomenon discussed in this paper:

First, the apparent conflict between research empires and individuals is not a conflict: it is a *balance* that serves the institution as a whole.

Second, the idea that one can predict research self-organization on the same basis as design in nature and engineering is worthy of discussion, especially among researchers.

Finally, or I should say firstly, those who coerce their colleagues into large groups (to generate funding, and to beef up their own CVs) are acting against the self-organizing *nature* of the institution, i.e., against the global interest. Complete coalescence into large groups does not happen and will not happen.

ACKNOWLEDGMENTS

This work was supported by a grant from the National Science Foundation for research on the Constructal Theory of Social Dynamics. I acknowledge with gratitude the continued advice received from Prof. Angèle Kremer-Marietti of the University of Picardie "Jules Vernes," Amiens, France.

REFERENCES

[1] Comte, A., *Cours de philosophie positive*, Présentation et notes par Michel Serres, François Dagognet, Allal Sinaceur, Hermann, Paris, 1975, tome I, p. 45 (deuxième leçon).
[2] Turner, J.S., *The Tinkerer's Accomplice*, Harvard University Press: Harvard, MA, 2007.
[3] Miguel, A.F., Constructal pattern formation in stony corals, bacterial colonies and plant roots under different hydrodynamic conditions. *Journal of Theoretical Biology*, **242**, pp. 954–961, 2006.
[4] Biondini, M., Allometric scaling laws for water uptake by plant roots. *Journal of Theoretical Biology*, **251**, pp. 35–59, 2008.
[5] Reis, A.H., Miguel, A.F. & Aydin, M., Constructal theory of flow architecture of the lungs. *Medical Physics*, **31**, pp. 1135–1140, 2004.
[6] von Herbing, I.H., The physiological basis for metabolic scaling in animals: a developing perspective. *Comparative Developmental Physiology. Contributions, Tools, and Trends*, eds S.J. Warburton *et al*., Oxford University Press: Oxford, UK, pp. 83–98, 2006.
[7] Miller, P., Swarm theory. *National Geographic*, pp. 126–147, July 2007.
[8] Bejan, A., *Advanced Engineering Thermodynamics* (2nd ed.), Wiley: New York, 1997.
[9] Bejan, A., *Shape and Structure, from Engineering to Nature*, Cambridge University Press, Cambridge, UK, 2000.
[10] Poirier, H., One theory explains the intelligence of nature. *Science & Vie*, **1034**, pp. 44–63, 2003.
[11] Reis, A.H., Constructal theory: from engineering to physics, and how flow systems develop shape and structure. *Applied Mechanics Reviews*, **59**, pp. 269–282, 2006.
[12] Bachta, A., Dhombres, J. & Kremer-Marietti, A., *Three Studies on the Constructal Law of Adrian Bejan*, L'Harmattan: Paris, 2008.
[13] Bejan, A. & Merkx, G.W., eds., *Constructal Theory of Social Dynamics*, Springer: New York, 2007.
[14] Bejan, A., Lorente, S., Miguel, A.F. & Reis, A.H., Constructal theory of distribution of city sizes (Section 13.4). *Advanced Engineering Thermodynamics*, 3rd edn., ed. A. Bejan, Wiley: Hoboken, 2006.
[15] Bejan, A., Why university rankings do not change: education as a natural hierarchical flow architecture. *International Journal of Design & Nature*, **2(4)**, pp. 319–327, 2007.
[16] Soler, J.J., Moller, A.P. & Soler, M., Mafia behavior and the evolution of facultative virulence. *J. Theor. Biol*., **191**, pp. 267–277, 1998.

[17] Clark, B.R., The many pathways of academic coordination. *Higher Education*, **9**, pp. 251–267, 1979.
[18] Chaput de Saintonage, M. & Pavlovic, A., Cheating. *Medical Education*, **38**, pp. 8–9, 2004.
[19] News: Italy continues R&D reforms. *Nature Medicine*, **4(9)**, p. 993, 1998.
[20] Xu, J. & Chen, H., The topology of dark networks. *Communications of the ACM*, **51(10)**, pp. 58–65, 2008.
[21] Bejan, A. & Lorente, S., *Design with Constructal Theory*, Wiley: Hoboken, 2008.