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STRUCTURE AND DYNAMICS OF SCIENTIFIC NETWORKS. PART I: FUNDAMENTALS OF THE QUANTITATIVE MODEL OF TRANSLATION

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The fundamentals have been developed for a quantitative theory on the structure and dynamics of scientific networks. These fundamentals were conceived through a new vision of translation, defined mathematically as the derivative or gradient of the quality of the actors as a function of the coordinates for the space in which they perform. If we begin with the existence of a translation barrier, or an obstacle that must be overcome by the actors in order to translate, and if we accept the Maxwell-Boltzmann distribution as representative of the translating capacity of the actors, it becomes possible to demonstrate the known principle of "success breeds success." We also propose two types of elemental translations: those which are irreversible and those which are in equilibrium. In addition, we introduce the principle of composition, which enables, from elemental translations, the quantification of more complex ones.

Introduction

It is widely accepted that science is a network of interacting entities or actors. To represent these relationships graphically on a map, the concept of cocitation[1] was initially proposed, followed by the coword analysis.[2–4] Finally, science is considered a network that can be quantified mathematically by either of the above methods.

Both in the 1980s and 1990s Latour's translation model was adopted.[5,6] According to this model, the facts are constructed and transformed according to the interests and positions advocated by the researchers and institutions involved. The network is a

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consequence of the "translations," both in its linguistic sense (transformation of meanings) and in its geometric sense (transformation of positions).

There are tests that indicate that the network evolves in a continual pursuit of equilibrium in terms of specific structures locally interconnected or centres of interest which are clearly differentiated from the rest.[2,7] *Ruiz-Baños* has developed a mathematical model of the structure pertaining to scientific networks, which is based on the above concepts and which completely fits the values observed.[8]

Objective

In Part I of this study, we shall develop a mathematical theory capable of accounting for the structure and dynamics of scientific networks. This theory is based on the translation model of *Latour*, who conceived of science and the construction of facts as an uninterrupted process of transformations and a game of interests. To quantify the translations, we shall follow the line begun in the work of *Ruiz-Baños* and introduce new concepts, some taken from the natural sciences.

The construction of science

Models of the construction of scientific knowledge rely in general on the idea that science is a corpus of knowledge in which statements are consistent with one another. This corpus is related to the idea of, and meant to represent, the ultimate reality. In other terms, science is perceived as the revelation of nature. The structure of the corpus grows according to the principle of overall consistency, by which a new statement fits within the established context. It is thus from this standpoint, that the first bibliometric researchers compared all new fields of research to an ore deposit.[9] The emergence of a new paradigm[10] (concerning the origin of revolutionary science) can lead to the reconstruction of the entire edifice and lead in turn (even transforming itself into conventional science) to a system of new statements. We can consider this process to be a fractal process of diffusion limited aggregation,[4] in the same way that lodes of particles attract other particles. That is, the larger the lode, the more it grows, while deepening the same structure. From an economic view, it is like a process of accumulating advantages, each successful invention calls for others, as a researcher's first success provides funds for a second.

Here, we shall take an approach which does not consider science as being constructed outside society, but rather as being an integral part of human activity. Far from the "grand partage",[12,13] we consider that science in the making is "hot", made of passion, and that society is related, at least in part. Within the frame of scientific knowledge, the human actors are in translation communication,[2] that is, they seek to satisfy their needs through social objects, following progressively longer routes.[14] For example, the electric milking machine represents this objetcs; rather than being an independent construct, it takes its place within a network of social activities.

Within the context of the networks by which scientific problems are formulated, called problematic networks, the social objects are in translation communication with each other. For example, research into autism and its treatment can be interpreted as research into medicines, and this in turn can be expressed as research into endorphins, insofar as autism can be characterized by an excessive level of endorphins. To learn more about the appearance of endorphins is a means of understanding more about how the medicines work. The two areas of research are interdependent, in both senses of the word. In fact, to understand more about how the medicines work is also a way of knowing more about the production of endorphins. In this case, we can state that the translation is balanced, in that each partner-actor achieves his own interest. Likewise, archaeological science itself is an area of resources by virtue of its knowledge, know-how, researchers and journals. It can translate these resources into research devoted to increasing knowledge of trade in the Mediterranean. For example, the study of amphoras can help in the understanding of ancient wine trade. Conversely, knowledge about trade in the Mediterranean can foster progress in archaeology. Work on amphoras in relation to wine trade can result in new techniques for dating and examining amphoras in general.

Translation is thus a transformation of resources with the intent of applying these to other problems, to increase the possibilities of organizing the world, a process which we named elsewhere "the increase of negentropy".[15] This concept concerns the extension of the network of knowledge and know-how to other areas of action.

A technique to connect these new areas of action to a given discipline is the analysis of associated words, generating themes or clusters of key words, the expression of research topics in translation with one another.[3] In this approach, the words are taken not for their conventional meaning, as in a semantic analysis, but rather for the relationships they establish between actors. These words are the expression of the technical culture shared by researchers and represent simple parameters accounting for the "spaces" within which the processes of translation are deployed. Citations between researchers constitute other such parameters. However, language is the only communal means of identification between entities separated a priori by scientific culture, such as theoretical concepts, instruments or practices which the process of translation attempts to merge and thereby create completely new hybrid entities, as in the joining, for example, of a spectrometer and ionizing radiation in order to gain better knowledge of polymer crystallization. This displays cultural objects (physical instruments, but also methods, concepts, etc.) and subjects culturally defined according to the norms of technical culture (the characterization of the actors involved culturally in a situation such as the assumption of a virus behind the symptoms of an illness).

To function successfully, a translation must jump the barrier of a translation. Thus, if it is not common to use submarine archaeology to study Mediterranean trade, the researcher will have to, for example, convince his funders of the possibility of discovering the Lighthouse of Alexandria with diving equipment. For this, he has at his disposal a potential or ability to translate, which is dependent on the credibility which he has developed through prior research.

Translation can also be seen from a statistical perspective. The greater the barrier of the translation, the fewer the number of researchers will be able to jump it. The more an actor's ability to translate is increased, the more numerous his contributions will become. Finally, the more central the problem, that is to say, the more it translates other problems, the more attractive it will be. The more the translations are solidly established, the more apt they will be to apply to other problems. The analysis of associated words makes precisely the statistical situation of the topics or themes of research appear from this viewpoint.

Mathematical concept of translation

Let a sociocognitive network be formed by N actors. The actors are defined by words and by qualities. A *quality* is that property presented, to a greater or lesser degree, by a group of actors and which differentiates them from the rest or from other groups of actors. Qualities are, for example, "to be published", "to be cited", "to be a key word", etc., and can be quantified by counting the number of articles published, the number of citations received or the number of articles indexed, respectively. Finally, a quality is proportional to a count of the actors.

Let us accept that qualities can be expressed as a mathematical function,

$$Q=f(x,y,z,...) \tag{1}$$

where Q: quality
x, y, z: coordinates.

The coordinates x, y, z... refer to *space*, or stage, where the actors perform. Thus, we can speak of a space of published articles, distinct from the space of the articles yet to be published; or a space of journals, authors, etc.. Spaces can be *temporal*, with a time coordinate, or *geometrical*, with coordinates referring to different positions within the network or to arrangements or ranges, according to the intensity of the quality considered.

The dynamics of networks always imply continual transformation, the actors modifying their definitions and interactions with others. These transformations, both in their sense of linguistic change in definition as well as their geometric sense of alteration of relationships, are what *Latour* called "translation."

Here, we mathematically define translation, T, as the variation or modification of the quality, Q, which defines an actor or set of actors, as a function of the coordinates of the space in which they act. As qualities are proportional to a count of the actors, the translation is defined also as the variation in the number of actors, as a function of the spatial coordinates.

If the space is one-dimensional of coordinate x, the translation of the actors, $T(x)$, will therefore be the derivative of $Q(x)$ with respect to x.

$$T(x) = \mathrm{d}Q/\mathrm{d}x \tag{2}$$

If the space is multi-dimensional, of coordinates x, y, z, etc., the translation of the actors will be according to each of these coordinates, that is, the gradient of the quality function Q $(x, y, z,...)$:

$$\mathrm{T} = \nabla Q = (\partial Q/\partial x)\mathbf{i} + (\partial Q/\partial y)\mathbf{j} + (\partial Q/\partial z)\mathbf{k} + \ldots \tag{3}$$

where **i**, **j** and **k** are the unit vectors of each of the coordinate axes.

In addition, let us accept that upon one actor or a set of actors, two or more translations can act, either in a successive or simultaneous form, this multiple action being called a *complex translation*. In the following sections, we elaborate the mathematical concept of translation.

Translations in equilibrium

Concept

Let an actor or set of actors, whose quality we shall denote as A, be translated into a new actor or set of actors, whose quality we denote by B. Let us represent the process of translating A into B in the following form:

$$A \longrightarrow B$$

to be read as "A translates into B."

This translation process is reversible, so that now we write:

$$A \rightleftarrows B$$

With this notation, we refer to the equilibrium that is established between the actors of quality A and the actors of quality B. The equilibrium is characterized by to be:

a) *dynamic*, that is, for each actor A translated into a new actor B, there is another actor B which is translated and occupies the place vacated by A. This process is never interrupted, and therefore the equilibrium does not represent the end of the translations, but rather the translating activity in one direction is matched by the translating activity in the other.

b) The translating process implies effort, the overcoming of a difficulty, the jumping of a wall, which we shall call *translation barrier*, W_T. This barrier comprises, for example, difficulties to surmount by necessary research and writing in order to publish a scientific article.

c) Each actor contains a certain *translation capacity*, C_T, this signifying the set of properties which enable an actor to translate with greater or lesser ease. If the translation capacity of a given actor exceeds the value of the translation barrier, the translation will be made. Contrarily, if the capacity value is less, the translation will not for the moment be made. A large translation capacity can be ascribed to a good article, a hard-working scientist, a research centre that publishes prolifically, or a research line that displays great dynamism.

Let us examine some examples of equilibrium:

a) Let there be the quality "to be the most central actor in the network." If an actor is the most central of all, and at a given moment loses this quality, another will immediately occupy his position, since there must always be one which is more central than the others. It would be absurd for none to be the most central one. With all certainty, this new most central actor would lose this quality and then another would occupy the position, this type of translation continuing indefinitely. In addition, we must emphasize the most central position is not occupied randomly or arbitrarily, but requires effort to achieve. The central position is gained only by that actor who, in terms of translation qualities and capacity, manages to relate most with the other actors.

b) Let there be the quality "to be cited." If an actor (an author, an institution...), is no longer cited, it is because citations are directed towards other actors. That is, equilibrium is established when some actors are cited at the cost of others and vice versa. In addition, this process of citation is dynamic, since an actor who is not cited today can be cited tomorrow, but perhaps not the next day. Overall, the percentage of citations remains stable, although there is a continual flow of non-cited actors to cited ones and a compensatory flow in the opposite direction.

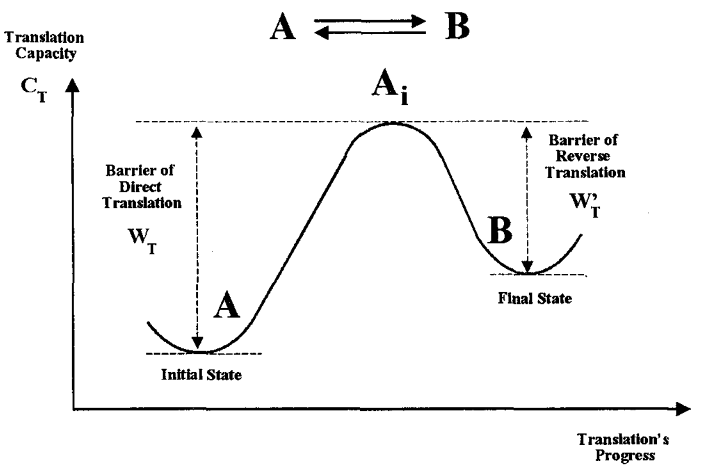

Fig. 1. Mechanism of the translation

In Fig. 1, the abscissa axis represents the progress of translation, and the ordinate axis the translation capacity. The actors A have a basic or inherent translation capacity and are at least situated at the initial stage, plus a translation capacity due to their qualities or activity that situates them above the translation barrier. The fraction of all the actions that have equal capacity to that of the translation potential are represented by A_i. We should stress that the translation barrier of the process which takes A to B, W_T, is not usually equal to the barrier of the contrary process of B to A, W_T'.

Three cases, therefore, can be given:

a) $W_T < W_T'$

As the step of A to B is easier than B to A, the equilibrium will move towards the right, in such a way that the quality B will be greater than the quality A, that is, there will be more actors of type B than of type A.

$$A \underset{\leftarrow}{\longrightarrow} B$$

b) $W_T = W_T'$

The translation in both directions offers the same difficulty, and thus we would expect an equal number of A and B actors.

c) $W_T > W_T'$

The direct translation is more difficult than is the reverse translation, and therefore the quality A will be more intense than B, or, in other words, there will be more A actors than B. This equilibrium moves to the left.

$$A \overset{\rightarrow}{\longleftarrow} B$$

Figure 2 shows the curves of the equilibrium translations, both in the case of movement to the right and movement to the left.

Quantification of equilibrium

The translation of equilibrium, $T(x)$, can be quantified, according to the definition proposed above, by evaluating the overall variation in the quality of A in the process, that is, the variation of the number of type-A actors.

$$T(x) = \{\text{Overall variation of A}\} \quad (4)$$

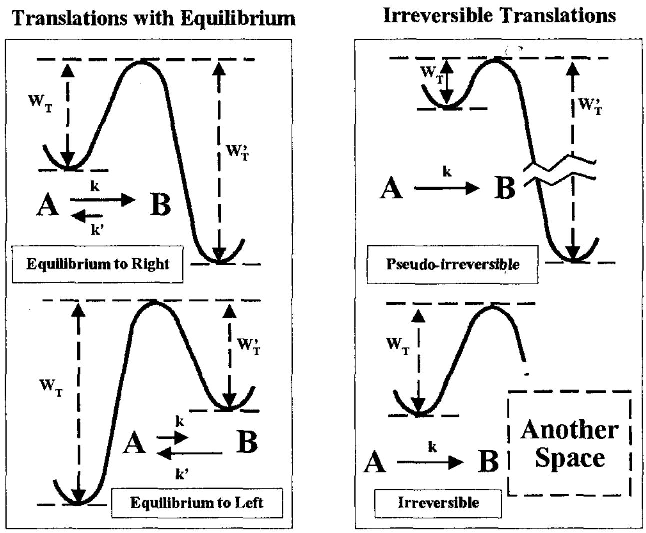

Fig. 2. Mechanism of elemental translations

As A and B are in equilibrium, it is evident that A diminishes by its translation into B, but augments simultaneously by the translation of B into A. This balance can be represented as follows:

$$\{\text{Overall variation of A}\} = \{\text{Diminution of A: A}\rightarrow\text{B}\} + \{\text{Increase of A: B}\rightarrow\text{A}\} \quad (5)$$

We shall therefore determine each of the terms of the above expression.

Overall variation of A. By the definition of translation in a one-dimensional space, and in accordance with Eq. (2), the overall variation of A is the derivative of A with respect to the x coordinate.

$$\{\text{Overall variation of A}\} = \mathrm{d}A/\mathrm{d}x \quad (6)$$

Depending on the space in which the actors perform, the coordinate x will be temporal or purely geometric in character.

Decrease of A by translation into B. If A_i represents the number of type-A actors which reach the translation barrier, W_T, (Fig. 1), then the more that possess this translation capacity, to a greater extent, the more the process should be developed. The diminution of A is proportionate to A_i.

Now a problem arises: if we know the number of total actors, how many have a translation capacity equal to W_T ? What is the value of A_i?

$$\{\text{Diminution of A: A}\rightarrow\text{B}\} = (\mathrm{d}A/\mathrm{d}x)_{\mathrm{A}\rightarrow\mathrm{B}} = -aA_i \tag{7}$$

Of the possible distributions, it appears reasonable to use those which offer us quantum physics related to particles (actors) which can reach various energy levels (translation capacity). These are:

a) Maxwell-Boltzmann,

b) Bose-Einstein and

c) Fermi-Dirac.

The distributions of b) and c) are applied to the case of indiscernible particles, that is, impossible to distinguish from one another. The first, on the other hand, applies to discernible particles. In our case, the actors are clearly defined and are completely differentiated from each other, and therefore we choose the Maxwell-Boltzmann distribution as the most appropriate.

According to this distribution, for a total of A actors, the number of them (A_i) that will reach the translation barrier, W_T, is determined by the equation:

$$A_i = A\, \mathrm{e}^{-mW_T} \tag{8}$$

If we substitute in Eq. (7):

$$\{\text{Diminution of A: A}\rightarrow\text{B}\} = (\mathrm{d}A/\mathrm{d}x)_{\mathrm{A}\rightarrow\mathrm{B}} = -a\mathrm{A}\,\mathrm{e}^{-mW_T} \tag{9}$$

and if we call:

$$k_1 = a\mathrm{e}^{-mW_T} \tag{10}$$

where k_1: translation constant, we get:

$$(\mathrm{d}A/\mathrm{d}x)_{\mathrm{A}\rightarrow\mathrm{B}} = -k_1 A \tag{11}$$

which is the mathematical expression of the known principle of "*success breeds success*", in this case "success" being the disappearance by translation of the A actors.

Increase of A by translation of B. In a similar way as in the preceding section, we can demonstrate that:

$$(\mathrm{d}A/\mathrm{d}x)_{\mathrm{B}\rightarrow\mathrm{A}} = k_2 B \tag{12}$$

where now:

$$k_2 = b\,e^{-mW_{T}'} \tag{13}$$

Differential equilibrium model. Taking into account Eqs (6), (11) and (12), we now write the expression in Eq. (5) in the following form:

$$(dA/dx) = -k_1 A + k_2 B \tag{14}$$

This equation represents the differential equilibrium model, since it expresses what the variation of A depends upon. Specifically, A decreases proportionally to itself and increases proportionally to B.

Equilibrium is reached when A neither increases nor decreases in overall terms, although it does continue the unbroken process of translating A into B and vice versa. Mathematically, equilibrium is reached when:

$$(dA/dx) = 0 \tag{15}$$

then:

$$k_1 A = k_2 B \tag{16}$$

Solving:

$$k_1/k_2 = B/A = K_e \tag{17}$$

In equilibrium, the actors A and B remain in constant proportion, which we shall call the equilibrium constant, K_e. The dynamic character is evident in that K_e depends on the translation constants k_1 and k_2.

When the equilibrium is moved to the right, $k_1 > k_2$, and therefore K_e is high. Contrarily, when the equilibrium is moved to the left, $k_1 < k_2$ and K_e is small.

Integral equilibrium model. The integration of Eq. (14) enables us to determine the values of A and B in all their extension, temporal or geometric, of the translation. As this is a differential equation with two dependent variables, we must resort to another that allows us to put B in the function of A. In fact, at any moment, the sum of A plus B will be constant, A_0.

$$A + B = A_0 \tag{18}$$

In this way, Eq. (14) is transformed as:

$$(dA/dx) = -k_1 A + k_2(A_0 - A) \tag{19}$$

Performing the operations:

$$(dA/dx) + (k_1 + k_2)\,A = k_2 A_0 \tag{20}$$

which is the linear differential equation, solvable by the constant variation method of Lagrange. The solution is:

$$A = e^{-\int (k_1+k_2)dx}\left(\int e^{\int (k_1+k_2)dx} k_2 A_0 dx + C\right) \tag{21}$$

$$A = (k_2 A_0)/(k_1 + k_2) + ce^{-(k_1 + k_2)x} \tag{22}$$

It is necessary to identify the constant C. If $x = 0$:

$$A_0 = (k_2 A_0)/(k_1 + k_2) + C \tag{23}$$

then:

$$C = A_0\,(k_1/(k_1 + k_2)) \tag{24}$$

Consequently, substituting in Eq. (22), we get the integral expression of A:

$$A = A_0/(k_1 + k_2)\,(k_2 + k_1 e^{-(k_1 + k_2)x}) \tag{25}$$

Taking into account Eq. (18), we find that the value of B is then:

$$B = A_0/(k_1 + k_2)\,(k_1 - k_1 e^{-(k_1 + k_2)x}) \tag{26}$$

Eq. (25) and (26) represent the integral model of the equilibrium translations. We find that the qualities A and B are functions of the x coordinate, as proposed in Eq. (1). We confirm also that when x tends towards infinity, the quotient between Eq. (26) and (25) is constant and equal to the equilibrium constant, K_e, Eq. (17).

In Fig. 3, we see that after a pre-equilibrium period, low x, a situation develops in which A and B remain constant. Equilibrium is reached when x is sufficiently high.

Irreversible translations

Concept

Translations are irreversible when they present no apparent equilibrium. These can be of two types:

a) Pseudo-irreversible translation. This type occurs when one of the translation barriers is much larger than the other, in such a way that the process moves almost completely in one direction and movement in the opposite direction is practically undetectable.

When $W_T <<< W_T'$:

$$A \longrightarrow B$$

b) Irreversible translation of space change. This irreversibility occurs when the actor of quality A, on overcoming the translation barrier, reaches a new translation space. For example, let there be the scientific work space with the quality "not to be published," and with these the set A, belonging to this space. When these works surmount the translation barrier (writing of the texts, critical analysis of the authors, analysis of the journal's review committees, modification of the original texts, etc.) they proceed to the space of the published scientific articles. A published article can never lose the quality of being published, translating now within the new space and never to return to the original situation.

Figure 2 also shows the translation curves which we have defined.

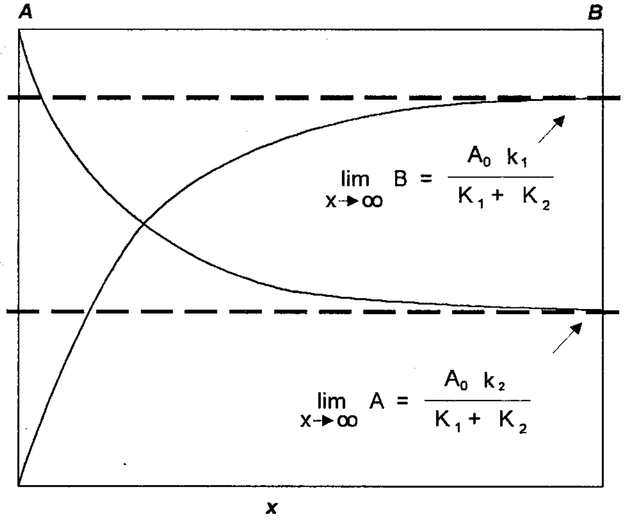

Fig. 3. Equilibrium translations. Curves of the number of actors as a function of the coordinates

Quantification of irreversible translations

If the translation barrier of the direct process is much less than that of the reverse process, of Eqs (10) and (13), it is deduced that k_1 must be much greater than k_2. In this case, in Eq. (19), the term with k_2 is negligible versus the term with k_1. The result is the following differential expression for irreversible translations:

$$\mathrm{dA}/\mathrm{d}x = -k_1\mathrm{A} \tag{27}$$

The equation is of separable variables of immediate integration:

$$\int_{A_0}^{\mathrm{A}} \frac{\mathrm{dA}}{\mathrm{A}} = -\int_0^x k_1 \mathrm{d}x \tag{28}$$

If we accept that k_1 is constant, the integral expression of an irreversible translation which extends from the position $x = 0$ to the position of $x = x$ is a negative exponential:

$$\mathrm{A} = A_0\, \mathrm{e}^{-k_1 x} \tag{29}$$

Figure 4 shows the curve typical of a translation of this type. We find that the value of A falls continually from A_0 to a null value when x tends towards infinity.

If in the translation of A into B, where B does not become translated, the value of k_1 is extremely high, the translation is so immediate that we can consider the facts to be accepted without controversy at all, and are therefore considered black boxes: the determinant will be the diffusion of the black boxes and not the translation. Under these circumstance of extremely intense translation, we expect a behaviour of diffusion-limited aggregation (DLA) and thus with net fractality.[16] In our theory, the fractal aspect is not general, but rather a particular case.

Principle of translation composition

Real translations can be the combination, superposition, sum or, finally, the composition of two or more translations.[8] From this principle, similar to that pronounced by Galileo with reference to the composition of movements, we infer that it is possible to quantify quite complex cases of translation in appearance, considering that these are only the combination of others considered elemental. Figure 5 shows some examples of possible complex translations. We divide them into series translations when they occur successively, and parallel translations when they occur simultaneously. They can in turn be irreversible and in equilibrium, as well as simultaneous combinations of series and parallel types.

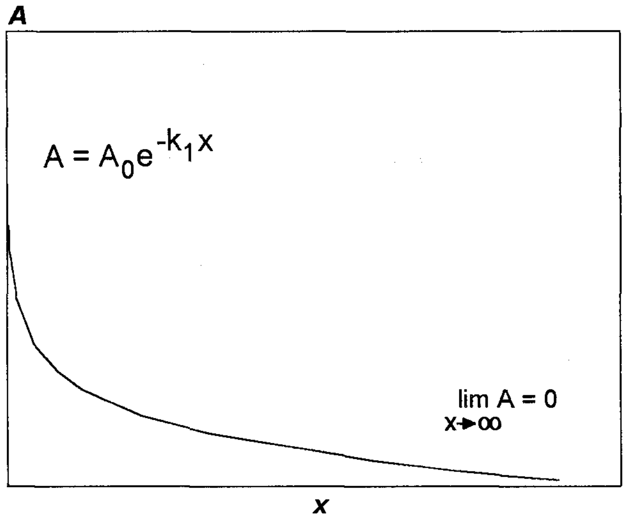

Fig. 4. Irreversible translations. Curve of the number of actors as a function of the translation coordinates

Natural models as particular cases of the translation model

The translation model proposed in the terms presented in the foregoing sections is conceived as a process of equilibrium between actors is carried out with the necessary concurrence of overcoming a difficulty known as the translation barrier. This process occurs in a space of temporal coordinates in the case of translations dependent on time (for example, growth of a network, obsolescence of science, etc.), or in a space of geometric coordinates (such as a range, a position more or less central within the network, etc.).

This model is inspired by two natural models, that of chemical transformations or reactions, and that of diffusion. That of the chemical reactions is based on the idea of equilibrium as described above, and also presents the necessity of overcoming a barrier for the reaction to take place, called the activation energy. On the other hand, the spatial coordinates are always time, since the chemical reaction occurs temporally. Parallel and complementary to this model, in nature we find a model of diffusion by which the particles move in space, seeking a situation of equilibrium characterized by a perfect mixture, or a complete homogenization. For this equilibrium to be attained, it is not necessary to overcome a barrier, nor is there a transformation of entities.

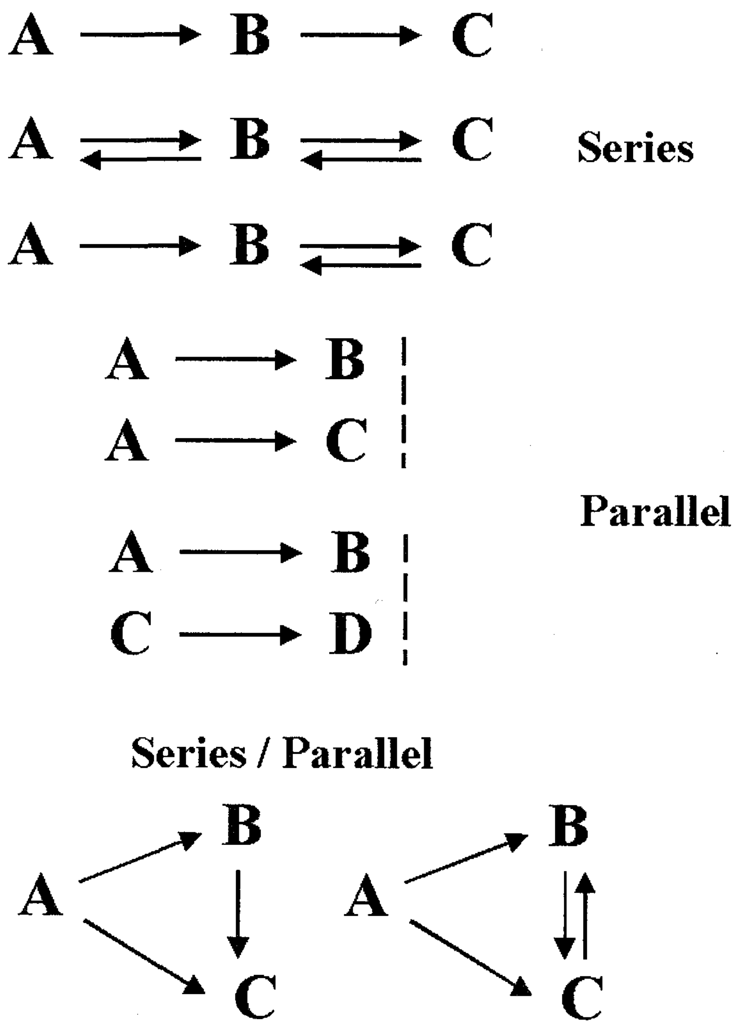

Fig. 5. Examples of complex translations

As the translation model in this work contains all the elements, and the natural models are only a part of these, we can conclude that these latter are particular cases of the more general case, which is translation.

Conclusions

In the present work, we have mathematically defined the concept of translation as the derivative or gradient of the quality function, depending on whether the translation space is one-dimensional or multi-dimensional. We have also introduced the concepts of barrier and translation capacity, and we have adopted the Maxwell-Boltzmann distribution to determine the number of actors with a translation capacity sufficient to surmount the translation barrier. From these concepts, we have deduced the following:

a) The principle of "success breeds success" is a result which is immediately and easily demonstrable for the above concepts.

b) It is possible to propose a differential model and from this deduce an integral model which quantifies the equilibrium translations. This equilibrium is reached when the translation coordinates tend towards infinity, a situation in which the number of actors remains constant and greater than zero. It is also dynamic, since it results from a direct translation and, simultaneously, another in the opposite direction.

c) We have defined irreversible translations of two types: pseudo-irreversible, in which the equilibrium is moved strongly in one direction, and the irreversible by a change of space. In either case, the integral model of the translation leads to a negative exponential function which is cancelled at infinity.

d) We present the hypothesis that when the translation constant is extremely high, and therefore the translation is immediate, the true controlling factor is the diffusion of black boxes. Under this circumstance, knowledge is constructed at random, from chaos, from one species of Brownian movement of actors which erratically approach points of attraction. This should bring about a fractal grouping called in the natural sciences "diffusion-limited aggregation" (DLA). In our theory, fractality is a particular case of the translation.

e) We propose a principle of translation composition which implies the existence of elemental translations (those of equilibrium and those of reversibility) and the rest of the translations, which would be a combination of the previous ones. We consider not only the series combinations but also the parallel ones, and with these we can account for any type of real translation.

In Part I of the present study, we have presented the fundamentals of our quantitative translation model. Its validity will depend on its capacity to explain the scientometric phenomena inherent in scientific networks. If we define the network using words, our model should be fit to the distribution of the frequency of these words (Zipf's Law), and from their distribution in groups (co-word analysis). Finally, if we define the network by co-citation analysis, it should also account for the distribution of the sizes of the clusters indicated by this methodology. In Part II of this work, we will examine these aspects in depth.

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