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A bridge between liquids and socio-economic systems: the key role of interaction strengths

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Abstract

One distinctive and pervasive aspect of social systems is the fact that they involve several kinds of agents. Thus, in order to draw parallels with physical systems one is led to consider binary (or multi-component) compounds. Recent views about the mixing of liquids in solutions gained from neutron and X-ray scattering show these systems to have a number of similarities with socio-economic systems. It appears that such phenomena as rearrangement of bonds in a solution, gas condensation, and selective evaporation of molecules can be transposed in a natural way to some socio-economic phenomena. These connections provide with a novel perspective for looking at social systems which we illustrate through examples. For instance, we interpret suicide as an escape phenomenon and in order to test this interpretation we consider social systems characterized by very low levels of social interaction. For these systems suicide rates are found to be 10 to 100 times higher than in the general population. Another interesting parallel concerns the phase transition that occurs when locusts gather together to form swarms which may contain several billion insects. What hinders the thorough investigation of such cases from the standpoint of collective phenomena that we advocate is the lack or inadequacy of statistical data; up to now socio-economic data were collected for completely different purposes. Most essential, for further progress, are the statistics which would permit to estimate the strength of social ties and interactions. Once adequate data become available, rapid advancement may be

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expected. At the end of the paper, we will discuss whether or not the ergodic principle applies to social systems.

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1. Introduction

Over the past decade econophysics and sociophysics have been developed by theoretical physicists mainly coming from statistical physics. Recent research in econophysics is comprised of a large body of empirical inquiries on topics which so far had been largely ignored by economists or sociologists. In addition, a number of theoretical tools developed in polymer physics, spin glass studies, Ising model simulations or discrete scaling were tentatively applied to problems in economics and sociology. This paper develops the idea that there is a connection between some of the phenomena studied in statistical physics and processes which occur in human societies. If persuasive, this argument would strongly support the claim (which is at the root of econophysics) made by physicists that the insight they have gained in studying physical systems can indeed be of value in the social sciences as well. Apart from this broad contention, our investigation will also tell us which phenomena are most likely to provide a good starting point for studying social systems in a fruitful way.

In the course of this paper we will see that it is the liquid state which seems to provide the best bridge to social systems. This is easy to understand intuitively. Crystallized solids have a structure whose regularity and symmetries have no match in social systems. On the other hand, gases are characterized by a complete lack of structure which is at variance with the existence of social networks. With their non-trivial and adaptive intermolecular interactions, liquids and more specifically solutions offer a better analog to socio-economic systems. Glasses, that is to say solids without crystal structure, could also be possible candidates but in the present paper we restrict our attention to solutions. Subsequently we give other, more technical, arguments in favor of a parallel between solutions and social systems.

Unfortunately, the liquid state is probably the less understood. It has been suspected for a long time (see for instance Moelwyn-Hughes, 1961) that the departure from ideal (or even regular) solution behavior is due to the formation of complex molecular assemblages even for non-ionic solutions. This was the central assumption on which Dolezalek's theory was based; however, it is only in recent decades that neutron and X-ray scattering as well as infrared spectroscopy provided a more accurate picture of such molecular clusters. The new picture which progressively emerged from these studies gave us an insight into microscopic mechanisms at molecular level. It is at this level that the parallel with social systems becomes natural. That is why, throughout this paper, we try to stick to molecular mechanisms and refrain from using such concepts as entropy, energy or temperature which become meaningful only at macroscopic level. So far, these concepts have no clear equivalent in social systems. At molecular level the only notions which make sense are those of distance and molecular attraction, stretching and vibrations, molecular assemblage, and so on. In the first part of this paper I describe some physical phenomena involving liquids in terms which can be easily transposed to social systems; in the second, I invite the reader to take the plunge and outline some social parallels.

The paper proceeds as follows. In Section 2, I recall that the key variable which accounts for a whole range of phenomena as diverse as boiling temperature, vapor pressure, surface tension, or viscosity is the strength of the intermolecular interaction. This is particularly true in the liquid state. This observation is a strong incentive to develop methods for measuring the strength of social ties. Then I explain why viewing the mixing of two liquids merely as an irreversible operation, which increases disorder prevents us from seeing the major role played by amalgamating and combining, two mechanisms which play a key role in biological as well as social phenomena. In Section 4, I consider the phenomenon of suicide in situations where one has a good reason to expect a low level of social interaction and accordingly high suicide rates. Then I devote a few words to social or biological situations which are similar to gas condensation or solvation. Needless to say, each of these phenomena would deserve a more detailed study. Our objective in this paper is to draw a possible agenda for future research rather than to offer detailed case studies.

Part I. Physical background

Studying social phenomena is often frustrating because for each law or regularity that one tentatively tries to propose there are usually many exceptions and outliers. The situation is fairly similar in physical chemistry. No model has a broad validity and exceptions abound even for the most basic effects. In this sense physical chemists are certainly better prepared to cope with social systems than for instance particle physicists or solid state physicists. The background presentation in the first part is entirely based on experimental evidence. The discussions I have had with colleagues in my lab convinced me that even experienced theoretical physicists may not necessarily be familiar with these facts and their interpretations. However, this first part may be safely skipped by physical chemists. The next section about interaction strength offers a pedestrian, and a fairly self-contained approach. In the section about the structure of liquids we limit ourselves to giving a number of important references about salient features.[1]

[1] A more detailed version of this section can be found in the preprint posted on the Cond-Mat website (no. 0405309).

2. The key role of interaction strengths

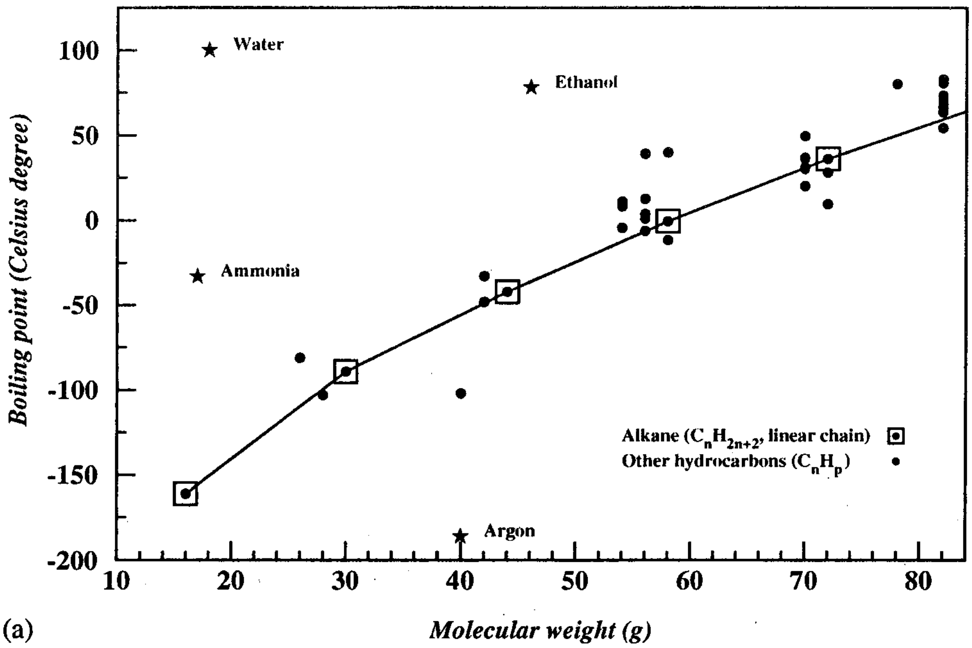
In statistical physics we know that, at least in principle, the properties of a system may be derived from its Hamiltonian. However, for systems like liquids this can only be done with great difficulty and often only numerically. The point we want to make in this section is much simpler. We show that the behavior of a system to a large extent depends only on the *strength* of the interaction; its precise form, whether it is a coupling between ions, permanent dipoles, induced dipoles or a mix of those interactions does not really matter from an experimental point of view. In what follows the interaction strength will be our key parameter.

Let us start with a simple question: why does ice melt at 0 °C and why does water boil at 100 °C? While molecular dynamics simulations are able to provide an answer, such explanations may not be completely satisfactory due to their lack of transparency. A simpler clue is to observe that the orders of magnitude of the fusion and boiling temperatures of liquids are determined by the attraction energy of the molecules. For instance, the H_2O molecules have an attraction energy of 10.8 kcal/mol, whereas for HCl which melts at −115 °C and boils at −85 °C, it is only 4.8 kcal/mol.

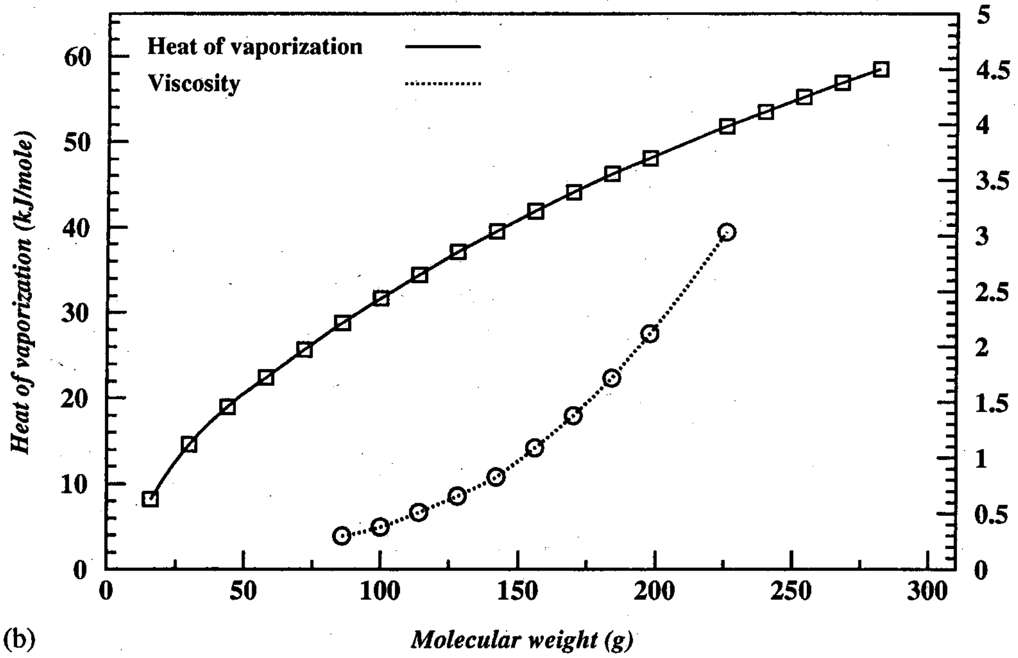
As a single example can hardly be convincing, Fig. 1a presents a family of cases. Apart from the outliers to which we come back later, the graph concerns only hydrocarbons and more particularly alkanes: C_nH_{2n+2}. As is well known, alkane molecules interact only through dipole-induced forces, the so-called London dispersion forces. These fairly weak forces exist between any pair of atoms. As a result the interaction between two alkane molecules is basically proportional to the length of the carbon chain, that is to say to the number n or equivalently to the molecular weight of the alkane. The squares correspond to experimental data for linear alkane chains, whereas the dots correspond to other hydrocarbons. The dots which correspond to isomers (same molecular weight) of a given alkane are of particular interest. These isomers have ramified carbon chains, a feature which to some extent changes the London forces between the molecules and results in differences of the order of 10% (when temperatures are expressed in Kelvin degrees). The stars show a number of cases characterized by different kinds of interactions. As we know both water and ethanol, CH_3-CH_2-OH have a dipole O_-H_+ which causes a fairly strong interaction through so-called hydrogen bonds. At the bottom of the graph the single atoms of argon have almost no interaction at all which results in a very low boiling point close to −200 °C. Incidentally, it can be observed that there is a close relationship between bond strength and bond length. For instance if we assume a potential corresponding to a ion–ion attraction and a hard core repulsive force proportional to $1/r^p$ ($p \sim 9$) the strength s of the bond is related to the distance R between the two ions by the relation:

$$s = \left.\frac{d^2 V}{dr^2}\right|_{r=R} = (p-1)\frac{e^2}{4\pi\varepsilon_0}\frac{1}{R^3}\ .$$

The key role of attraction strength is not limited to fusion and boiling temperatures, it extends to many other physical properties such as heat of vaporization, pressure of



(a)



(b)

Fig. 1. (a) *Boiling temperature as a function of intermolecular attraction*: For alkanes C_nH_{2n+2} with a linear chain, which are represented by dots surrounded by a square, the inter-molecular attraction is proportional to the number of the hydrogen atoms and hence also to the molecular weight $M = 14n + 2$. The trend portrayed by the solid line means that for longer carbon chains more thermal agitation is required in order to break the intermolecular bonds. The dots represent hydrocarbons C_nH_p whose intermolecular forces, are slightly different due for instance to branched carbon chain which results in boiling temperature differences of the order of 10%. The stars correspond to compounds whose molecular coupling are of a different nature, either much weaker (argon) or much stronger (ammonia, ethanol, water). *Source*: Lide [1]. (b) *Latent heat of vaporization and viscosity as a function of inter-molecular attraction for alkanes*: As explained in (a) there is a direct relationship between attraction strength and molecular weight. The solid line corresponds to the 20 first alkanes (except $n = 15$ which is missing in data tables); it describes the empirical relationship: $L_s(C_nH_{2n+2}) = 1.1 + 1.7n$. The broken line represents the viscosity; it is restricted to the alkanes which are liquid at room temperature, namely $n = 7, \ldots, 16$ ($n = 15$ is again missing). *Sources*: Lide [1], Moelwyn-Hughes [2, p. 702].

vapor, viscosity, surface tension, etc. Once again, for the purpose of illustration we consider the case of the alkanes. Fig. 1b shows that the enthalpy of vaporization and the viscosity of alkanes is determined by the strength of the intermolecular forces (i.e., molecular weight). As it would be pointless to compare the viscosity of gases with that of liquids we restricted the latter curve to the alkanes which are liquid at room temperature.

The relationships displayed by the curves in Fig. 1a and b have a clear intuitive interpretation. The stronger the interaction, the better the molecules are held together and the more kinetic energy it takes to disrupt the molecular assemblages that make up solids or liquids. In the same way, in a liquid with a strong interaction only the fastest molecules will be able to escape which translates into a low vapor pressure. As to viscosity, a strong interaction will make neighboring layers to stick more closely together which for liquids results in a higher viscosity.

In order to test this way of reasoning let us see if we can use it in order to predict the relationship between interaction strength and other physical properties such as the speed of sound. For sound to propagate, successive layers must be put into motion. Due to inertia, in order to put one layer into motion, the main factor is the weight of the molecule. If there are strong bonds between molecules two things will happen.

- In a given layer, the inertia effect will be increased because strongly coupled molecules will behave so to say as a massive, tightly knit cluster of molecules.
- The transmission of the perturbation from one layer to the next will be facilitated.

Which one of these effects will prevail is not obvious. Observation shows that the first effect prevails in gases. Thus, by comparing the speed of sound in methane, CH_4, and propane, C_3H_8, we see that it is smaller in propane even after the factor $\sqrt{M}$ due to the molecular weight has been corrected for. In other words, for gases the speed of sound decreases with stronger interactions. On the contrary, in liquids and solids it is the second effect which prevails as illustrated by the two following example.[2] (i) The speed of sound in liquid pentane, C_5H_{12} is 1012 m/s (at 25 °C and 1 bar). For heptane, C_7H_{16}, due to its higher molecular mass, one would expect a smaller velocity; yet it is higher at 1129 m/s. (ii) As one knows, diamond, a solid with very strong interatomic bonds has a velocity of sound of 12,000 m/s, one of the highest in any substance.

The previous discussion shows that even in cases where physical consequences of a strong interaction are less transparent than in the cases of Fig. 1a and b, this factor, nevertheless, plays an essential role.

If we try to understand what makes up molecular attraction, the picture becomes much more intricate. For instance, we know that the dipole moments of H_2O and

[2]Let us recall that for all materials, whether gas, liquid or solid, the speed of sound is given by $c = \sqrt{E/\rho}$ where ρ is the density and E the bulk modulus of elasticity $E = \Delta\text{pressure}/[\Delta\rho/\rho]$ which basically describes the hardness of the material. In the case of a gas E can be expressed as the inverse of the (adiabatic) compressibility $E = 1/[(\Delta V/V)/p]$ where V and p denote volume and pressure, respectively. In the case of a solid E is usually referred to as Young's modulus. The above formula says that the speed of sound is larger in harder or lighter materials.

HCl are 1.86 and 1.08 debye, respectively. However, the link between these moments and the molecular attraction is not straightforward for at least two reasons: (i) we know that molecular attraction does not only depend on the dipole moment but that the dielectric constant also plays a crucial role; different liquids may have very different dielectric constants; (ii) the dipole–dipole interaction is not the only force which plays a role; there are also London forces; as a matter of fact, for HCl, the London attraction is much stronger than the dipole attraction: 4.0 kcal/mol for the first and 0.8 kcal/mol for the second. In short, the closer we look at the system, the more involved the picture becomes. The next section provides another illustration of this rule.

3. The structure of liquids and their mixing

A statement which is often made by social scientists is that social systems are far more complex than natural systems. In truth, the difference seems to come from different description levels. Social scientists try to describe social phenomena at the level of detailed interpersonal interactions. At the corresponding level of intermolecular interactions, physical systems are also very difficult to describe and understand. The researches about the structure of liquids provide a good illustration. It is water which has been studied in the most thorough way, not only because of its obvious importance for life on our planet, but also because it displays a number of interesting conundrums. Throughout the 20th century, this has been a very active field of experimental and theoretical research. The interested reader is referred to the following landmark papers: Maréchal [3], Poole et al. [4], Soper et al. [5], Stanley et al. [6], Mishima et al. [7], Wall et al. [8] and to a recent review paper by Schmid [9]. Among the experimental techniques which were used one can mention: infrared and Raman spectroscopy, neutron and X-ray scattering. This is a point to which we come back in the last part of the paper. What makes the structure of water (as well as other liquids) complicated is the fact that to a large extent its molecules keep the same crystal-like organization as in ice.

If liquids have intricate structures, their mixings, not surprisingly, are complex phenomena as well (as illustrations see [45,47]). In physical textbooks the mixing of two ideal gases or liquids is represented in a very schematic way. Before mixing, two boxes contain molecules A and B, respectively; after mixing the A and B molecules are combined and distributed randomly in a single box. This picture which ignores interaction is not only simplistic it is also in a sense misleading. Indeed, in any real situation if the A and B molecules do not establish intermolecular bonds the two liquids will *not* mix. By considering ideal solutions for which interactions are neglected before as well as after the mixing, one misses a very important point, namely the fact that the mixing is a “creative” process in which new interactions and structures emerge. The most obvious way to realize that something non-trivial occurs when two liquids are mixed is to observe the temperature increase or decrease. For instance, the mixing of water with ethanol results in a temperature rise of about 5 °C accompanied by a volume contraction. (for chloroform and acetone the temperature rises more than 10 °C). In many cases, the mixing is accompanied by an increase in structural order (i.e., a *decrease* in entropy). This is for instance the case when methane dissolves in water. According to some recent studies [10–14] there are as many as 17 water molecules in the first hydration shell which forms around any individual molecule.

Attempts to bridge the gap between statistical physics and socio-economic phenomena usually come up against two difficulties. The first one, not often mentioned, is to know whether or not the ergodic hypothesis applies. The second is the fact that the notions of energy, temperature or entropy which are so central in physics have no obvious counterpart in social phenomena. That is why we carefully avoided using these notions. The mechanisms described in this first part have been explained in terms of attraction and movement of molecules, all of which can be transposed to biological or social phenomena. This is the purpose of the second part of the paper.

Part II. Social phenomena in the light of liquids

The main challenge in this part is to identify those (if any) social phenomena which can be better understood in the light of the notions presented in the first part. Needless to say, many kinds of social phenomena do not fall into this category. For instance, cultural or gender studies draw on notions which have no parallels in physics. There are, however, many important socio-economic phenomena which can be interpreted along the lines used in Part I. One can mention the following.

- In the first part we emphasized the connection between interaction strength and molecular rates of escape from a liquid. Any system whose members are held together by some cohesion forces but may occasionally escape provides a possible parallel. Table 1 gives a number of examples.
  For instance, if the system is a college or a university the retention rate of freshmen provides an indication about the balance between group cohesion and centrifugal forces. If the system is an army, the desertion or absent without leave (AWOL) rates provide a global estimate of the resultant of many forces such as patriotism, fear of being punished, conservation instinct, and so on. All the cases mentioned in Table 1 would provide interesting testing fields for the interpretation that we have advocated. Unfortunately, for most of them only scarce or fragmentary data are available. By a slight but natural extension it is possible to include suicide into the present category. The likelihood of not committing suicide represents a kind of retention rate. The main incentive for including suicide is the fact that in this case there are numerous statistical data. Naturally, suicide has been studied by sociologists for decades without any reference to physics; one may, therefore, wonder what difference it makes to adopt the present perspective. Instead of analyzing suicide statistics almost indiscriminately, the present perspective leads us to focus on situations where social ties are either very strong or very weak. By doing so we will be in a better position to grasp the key

Table 1
Retention dynamics in various institutions

Institution	Intra-institutional bonds	Type of escape
High school, College, University	Links with students, teachers, professors; attraction of qualified jobs	Dropout
Faith community, religious order	Links with rest of congregation, common faith	Decline in attendance
Army	Patriotism, discipline, renumeration	Desertion
Nation	Family ties, attraction of home country	Emigration
Society	Family ties, links with friends	Suicide

Note: The fact that one often observes a conjunction of substantial high school dropout rates with high suicide rates among teens seems to show that the interactions which account for these effects overlap to some extent. As an illustration, for the Oglala Sioux who live on Pine Ridge Reservation, South Dakota, dropout and suicide rates among teens are 6 and 4 times higher, respectively, than in the general population; for American Indians overall, the dropout and teen suicide rates are 35 percent and 37 per 100,000, respectively, 3 and 2.5 times higher than in the general population. In the second column we attempted to list some of the possible bonds that keep an individual attached to a given institution. This list, however, is based more on common sense than on genuine measurements. As a matter of fact, we do not yet know what is the respective importance of these links. For instance, we know that family ties are important in suicide, but we do not have a clear picture of the respective role of short-range versus long-range ties. What makes reliable measurements difficult is the fact that the level of exogenous shocks (which represent thermal agitation) is usually time-dependent and has, therefore, to be controlled for.
Sources: Reyhner [15], Olson [16], http://www.re-member.org

mechanisms (as opposed to incidental circumstances) of the phenomenon. The next section provides an introduction to this approach.

- The second physical phenomenon for which there are some natural biological and social parallels is the condensation of a gas, that is to say, the transition from a state in which the molecules are almost independent to a state where they form clusters characterized by substantial internal interaction and cohesion. Macromolecules, bacterias, protozoa, insects, animals or humans in certain conditions display tendencies to self-aggregation. Instead of considering each of these cases as separate, it may help our understanding to look at them from a unified standpoint. Two cases will be discussed which belong to this category of phenomena.
- The third physical phenomenon for which there is a natural sociological extension is the mixing of liquids. Amalgamation of different populations is a mechanism of fundamental importance. Under this heading one can consider the amalgamation of populations of peasants, merchants and craftsmen. Through the links of

cooperation and exchange that they establish, cohesion and productivity are greatly enhanced. Another important mechanism of amalgamation is the so-called melting pot mechanism by which a group of immigrants becomes integrated. Again, one may ask what benefit can be gained from considering these phenomena from the standpoint of statistical mechanics. In a physical solution the new bonds between solute and solvent are established in a matter of seconds if the solution is stirred by an external device, but it may take a much longer time if instead one has to rely on diffusion. Similarly, the time scale required by the amalgamation process very much depends upon the magnitude of the "mixing". It may take one or two generations in a city, but much longer in a mountainous region where the population density is low and contacts are rare. This parallel shows that in order to understand the dynamics of bond formation one must adopt an adequate time scale. For urban integration, 50 years may be an acceptable time period, whereas for low density regions two or three centuries would be more suitable. In short, through the analogy with physical phenomena we get a better understanding of how to set up the inquiry.

4. Suicide in a population with weak ties

In the late 19th century there have been numerous studies about suicide in many European countries. The following references (arranged in chronological order) constitute a select sample of the publications of that period, along with some more recent ones: Boismont [17], LeRoy [18], Cristau [19], Morselli [20], Legoyt [21], Masarick [22], Nagle [23], Durkheim [24], Krose [25], Bayet [26], Douglas [27], and Baudelot et al. [28]. All these studies of course took advantage of the fact that, thanks to the development of census offices, extensive demographical statistics became available in all industrialized countries. Among the aforementioned authors, the contribution of Emile Durkheim stands out because in contrast to most other authors he was not interested in why individual people commit suicide but from the start considered suicide as a social phenomenon. In the very first section of his book, he makes it clear that to understand suicide one should examine the web of connections and affiliations each individual has with the people around him. For Durkheim it is the failure of the family, church, and community of neighbors to provide effective forces of social integration which is at the heart of the problem. In short, Durkheim's perspective is very close to the standpoint of statistical physics that we presented in part I. Unfortunately, his message has been largely discarded and forgotten, to the point that nowadays most studies center on *individual* psychological causes.

In support of his thesis Durkheim presents a wealth of data for many different countries. However, for his argument to become really compelling and conclusive one would need a way to measure the strength of social ties in an objective and quantitative way. Instead Durkheim relies on common sense and intuition with the result that his proof remains somewhat tautological. For instance, even if it is natural to admit that bachelors have fewer family ties than people who are married and have several children, estimates based on an objective criterion are nevertheless needed.[3] Otherwise the observation that suicide rates are higher among bachelors cannot be quite conclusive. We must confess that our own methodology will have the same defect, only to some extent mitigated by the fact that the situations we consider are so extreme that "common sense" estimates need only to have the right order of magnitude. In the following we consider three situations of that kind.

4.1. People with schizophrenia

Schizophrenia is a severe mental illness characterized by a variety of symptoms including loss of contact with reality and social withdrawal. People with schizophrenia may avoid others or act as though others do not exist; for example they may avoid eye contact with others or may lack interest in participating in group activities. Clearly this is a situation where interpersonal links are severely weakened. It turns out that suicide rates among people with schizophrenia are 10–15 times higher than in the general population: a typical figure is 200 per 100,000 as compared to 15 per 100,000 in the general population.

4.2. Inmates

Persons who are arrested and jailed see links with family, friends, colleagues or neighbors suddenly severed. Of course, once in jail for some time, inmates are likely to build new ties for instance with other inmates, guardians, lawyers, chaplains or other persons who may assist them. One would expect, therefore, that it is in the first few days in jail that the disaggregation of social ties is the most severely felt. This prediction is matched by observation. Indeed, it turns out that suicide rates are particularly high during the first few days in jail. A study performed in 1986 about jail suicide in the US found that 51% of the suicides which occur in jail (as opposed to prison which in the US designates facilities for stay of over one year) happen in the first 24 h of incarceration.

Thanks to official data which are available on the Internet for New York State (New York State 1998: Crime and Justice Annual Report, http://criminaljustice.state.ny.us) we are able to compute an order of magnitude of the suicide rate in short-term detention facilities technically known as "lockups" where detainees usually stay for less than 72 h before being transferred to county jails. The reasoning goes as follows. On a single day of 1998 the average number of detainees in lockups was 473 (151 for New York City and 322 for the rest of New York State). Naturally, these detainees were not the same throughout but this is irrelevant for the present calculation. Over the whole year there were 6 suicides (2 in New York City and 4 in the rest of the state) which gives a rate of $6/473 = 1268$ per 10^5. If the same calculation is done for each year between 1990 and 1999 one gets an average suicide

[3] Consider the following counter-example. A bachelor who lives in the region where he grew up has family ties with his parents, brothers, nephews and nieces. In contrast, a father with a four children family who has had to move to another region, has family ties with only five persons.

rate of 903 per 10^5. Because a great majority of inmates are males, this figure should be compared to the suicide rate of men in the general population of New York State which for the period 1990–1998 was 13.0 per 10^5. The suicide rate in the first 3 days of detention was therefore 69 times higher, This order of magnitude is consistent with results obtained by other studies which analyzed suicide rate in the first days of detention (Table 2). As detainees form new links in jail, the suicide rate progressively declines. In county jails where inmates usually stay for periods of less than one year, the rate is about 10 times higher than in the general population. In state prisons, where inmates stay for periods of more than one year, the rate is almost the same as in the general male population.

Table 2 also provides data for some other countries. These data do not distinguish between short and long-term facilities. Most of the figures are between 100 and 200 which is consistent with the rates observed in US county jails.

How accurate and reliable are the data given in Table 2? This is certainly an essential question. An official report [29] found under-reporting of jail suicide in 1986, to be of the order 40 percent nationally, but with great differences between states. Thus, in New York State no under-reporting was identified (which is why we selected this state to compute the previous estimate), whereas in Alabama, Louisiana, Pennsylvania or Tennessee under-reporting was over 50 percent. As there are no reasons for and indeed no mention of over-reporting we can at least be assured that the figures which are made public provide trustworthy lower bounds.

In conclusion, the phenomena of suicide among people with schizophrenia or inmates seem to provide spectacular illustrations of the effect of a weakening of social ties on suicide (escape) rates. However, these situations may be seen with good reason as somewhat artificial in the sense that these groups are subject to illness or special living conditions imposed from outside. This is why we now turn to situations which can be considered as more "natural"; the observations refer to what happens when "traditional" societies come into contact with societies which are technically more advanced.

4.3. *Traditional societies in situations of transition*

Every time the social framework of a society undergoes overwhelming changes, there is a time of transition during which the old structures no longer work or exist and those which are better adapted to the new situation have not yet emerged. As a result, one would expect such periods of transition to be characterized by a low level of social interaction. When two liquids mix, the time it takes for the pattern of forces to rearrange and for the molecular structure to be reordered is probably to be counted in microseconds at the molecular level, and in seconds at macroscopic level (provided the two liquids get mixed). In a society the transition may take decades. The figures in Table 3 show that these situations are characterized by a substantial increase in suicide rates up to levels which are 3–4 times higher than in stable societies. These phenomena have many facets: familial, communal, demographic, economic, political, etc. In the rest of this section we focus our attention on the case of Micronesia for which one has fairly good statistical data.

Table 2
Suicide rates among inmates

	Type of institution	Time elapsed since incarceration (T)	Location	Time interval	Annual suicide rate (per 100,000)
1	Lockup	$T<72$ h	New York State	1990–1999	900
2	Lockup	$T<72$ h	South Dakota	1984	2975
3	Jail	72 h $<T<$ 1 year	Texas	1981	137
4	Jail	72 h $<T<$ 1 year	South Carolina	1984	166
5	Jail	72 h $<T<$ 1 year	US	1986	107
6	Jail	72 h $<T<$ 1 year	New York State	1986–1987	112
7	Prison	1 year $<T$	US	1984–1993	21
8	Not spec.	Not spec.	Belgium	1872	190
9	Not spec.	Not spec.	England	1872	112
10	Not spec.	Not spec.	Saxony	1872	860
11	Not spec.	Not spec.	Canada	1984–1992	125
12	Not spec.	Not spec.	New Zealand	1988–2002	123
13	Not spec.	Not spec.	England	1990–2000	112
14	Not spec.	Not spec.	France	1991–1992	158
15	Not spec.	Not spec.	Australia	1997–1999	175
16	Not spec.	Not spec.	Canada	1997–2001	102
17	Not spec.	Not spec.	Scotland	1997–2001	227
	Average (8–17)				218

Note: As a useful yardstick one can use the suicide rate among males in the United States between 1979 and 1998 which was about 20 per 100,000. Suicide rates of inmates are highly dependent upon the time, T, they have spent in prison since their incarceration. A detailed study based on 339 suicides that occurred in the US in 1986 found that 51 percent of the suicides occurred in the first 24 h of incarceration. This observation is consistent with the interpretation of suicide as resulting from a severing of social ties. In the statistics published in other countries than the United States, the time of incarceration is not specified. However, since inmates incarcerated for less than one year are in greater number than those incarcerated for longer durations, one would expect the former to predominate. Therefore it is not surprising that the order of magnitude of suicide rates is more or less the same everywhere (one exception is Saxony).
Sources: 1: DCJS Report [30, Tables 7,9,11]; 2. Hayes and Rowan [29, p. 4], 3–5. Hayes and Rowan [29, p. 52–53]; 6. DCJS Report [30, Table 1], Hayes and Rowan [29, Table 2]; 7. http://www.mces.org/Suicide_Prisons_Jails.html; 8–10. Legoyt [21]; 11. Correctional Service [31]; 12. Corrections Department, http://www.corrections.govt.nz [32]; 13. Her Majesty Prison Service [33]; 14: Baron-Laforet [34], Bourgoin [35]; 15–17. same as 12.

Micronesia, as it is defined by Rubinstein [37,49] from which we borrow most of the following information, comprises the Marshall Islands, and the Carolinas which now form the Federated States of Micronesia and the Northern Marianas. Most of these islands were occupied by Japan in 1914 and some of them were colonized by Japanese farmers. After World War II they became American Territories until they acceded to some form of autonomy in the late 1980s. In the 1950s and 1960s nuclear

Table 3
Suicide rates in populations in a state of transition

	Population	Gender or age specification	Location	Time interval	Suicide rate (per 100,000)
1	Blackfoot		US	1960–1969	130
2	Cheyenne		US	1960–1968	48
3	Papago		US	1960–1970	100
4	Indians	10–19	Canada	1986–1990	65
5	Natives	Male	Micronesia	1975–1990	50
6	Natives	Male, 15–24	Micronesia	1978–1987	129
7	Natives	Male, 15–24	Chuuk Islands	1978–1987	200

Note: As a matter of comparison the average suicide rate in the United States over the period 1979–1998 was 12.2 per 100,000 for both genders, 19.5 per 100,000 for males and 20.7 for males aged 15–24. The area considered in cases 5 and 6 comprises the Federal State of Micronesia (Chuuk, Kosrae, Pohnpei, Yap), the Marshall Islands and Palau. Blackfoot, Cheyenne and Papago are three tribes of American Indians. Basically, either for North American Indians or in Micronesia the suicide rate of young adults is at least 4 times higher than in the general population.
Sources: 1–3: Lester [36]; 4. http://www.hc-sc.gc.ca;5–7. Rubinstein [37]. Hezel [46].

tests and missile tests were conducted at Bikini, Eniwetok and Kwajalein located in the Marshall Islands. While alcohol consumption by the islanders had been regulated or prohibited under Japanese rule, these restrictions were lifted in the 1960s. Moreover, thousands of US Peace Corps Volunteers arrived, schools were built in every island and the economy began to shift from a subsistence economy based on family gardening and fishing to the one based on imported products and wage labor. Men played a central role in the former two activities and their place in society was more affected than women's activities which centered around preparing food and taking care of the house and children. Yet, in Fig. 2 it can be seen that suicide rates increased among men as well as women even if the latter did not exceed the level observed in industrialized countries.

How can we integrate and interpret these various changes in terms of social interaction? As we have already noted, to do this in a satisfactory manner would require either quantitative information about the frequency and intensity of interpersonal contacts and links, or a methodology (an equivalent to infrared spectroscopy) that would enable us to estimate interaction strengths. However, we can make two observations which are fairly revealing at least qualitatively.

(1) If interaction strength really plays a key role in this phenomenon, one would predict that the individuals who are most at risk are those who do not have strong family connections. This is true for suicide in a general way, but one would expect the effect to be much stronger in a situation where community bonds have been weakened. The transition period between childhood, characterized by strong ties with parents, and adulthood, characterized by strong ties with one's own wife and children, is a critical moment. In short, one would expect a high suicide rate among young adults. This is indeed what observation shows (Table 3). This effect can be expected in any society in transition, but in Micronesia it is to some extent amplified

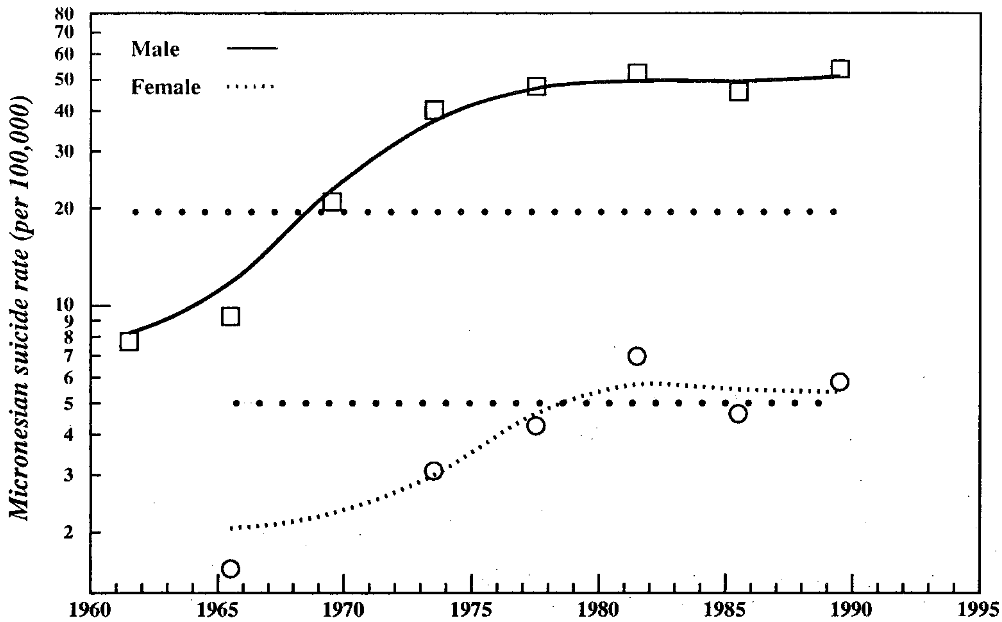


Fig. 2. *Suicide rate in Micronesia*: The area covered by these data comprises the island of Palau, the Federated States of Micronesia (which includes the Chuuk islands) and the Marshall Islands. Concomitantly with the shift from a subsistence economy to one based on imported food and wage labor, there has been a huge increase in suicide rates for both men and women. The dotted horizontal lines show the American average suicide rates for men and women. It is the 15–24 age group which has by far the highest suicide rate, a pattern which strongly differs from the age pattern in industrialized countries where suicide rate increases with age. It is of interest to note that in Micronesia the high school dropout rate is around 40 percent that is to say four times more than in the United States. *Source*: Rubinstein (1994) [37], Hezel [38].

because of two local factors. As it is (or at least was) considered taboo for a sexually mature boy to sleep in the same house as his sisters, teenagers used to move to community men's houses which they would share with extended family relatives. But in many islands these community houses are no longer kept up, with the result that young men do not have places where they can conveniently stay at this critical juncture. The second aggravating circumstance is related to the custom of adoption. In Micronesia, adoption was a widespread custom and a central pillar of family life. Like godfathers or godmothers but in a much stronger sense, the adoptive parents were a major constituent of the enlarged family. However, this institution has been imperiled both by the decay of traditional culture and by the rapid population growth. With a large number of children in each family there is less incentive for adopting. The clear effect of the decay of adoption was to reduce the links between teenagers and adults.

(2) Micronesia consists of more than 100 islands. As they have not been affected to the same degree by social change, we are in a good position for making comparative observations. Rubinstein [37] mentions that suicide is less frequent in rural outer islands where traditional ways of life were maintained to some extent. For instance, in the central island of Chuuk the average suicide rate of young males (15–24) was 207 per 10^5, whereas 500 km to the east in the Pohnpei and Kosrae islands it was only 93 per 10^5.

At this point, we do not know if the factors that we have just described are really the main mechanisms that account for the high suicide rates. In order to confirm (or confute) these conjectures other similar cases must be investigated in a comparative perspective.

5. Condensation phenomena

Particularly abundant rain in the area of central or northern Africa may result in a population of locusts which is in greater number than in ordinary years. It seems that once the density of locusts reaches a critical level a phase transition occurs which leads to the formation of swarms of locust which may contain billions of insects and have a duration of several years. In this process, locusts undergo slight physical changes (change in color, development of a gland for the release of a specific pheromone) which lead entomologists to describe them as a distinct subspecies (which they call a phase), namely *locust gregaria* as opposed to *locust solitaria* [39]. In order to better understand the factors which determine the transition from one phase to the other Jacobus Faure raised population of locusts in adjacent cages. It is worth reporting how he describes a cage containing *locust solitaria* in one half and *locust gregaria* in the other. He says, "whereas an individual isolated in one half of a cage leads a life of lazy idleness, its fellows in the other compartment separated by a gauze partition only, live a life of intense activity that could perhaps best be described as a frenzied effort to escape from some relentless, inwardly pursuing force". This observation suggests that the level of interaction and activity is greatly increased in the swarm state.

After having established that it is the crowding that leads to the formation of swarms, Faure went on to show that inter-specific crowding has the same effect as intra-specific crowding. In other words, the enhanced interaction that leads to swarm formation seems to be unconnected to a particular species of locusts.

The second example that we wish to mention of a transition analog to a condensation of a gas into a liquid is linked with the phenomenon of territorial conquest by clans of nomads that occurred repeatedly in central Asia. At least five episodes have been recorded by historians between the first and 17th century. In their "gaseous" state the clans wander more or less randomly over the vast land expanses of the steppe and have only minimal interaction with one another. Then, all of a sudden for no obvious reason, the various clans gather around a leader whether it is Attila, Genghis Khan or Tamerlane. On such episodes our historical information is mostly limited to anecdotal evidence. We largely ignore the reasons which trigger these events;[4] however, once started, it may have worked like a chain reaction in the

[4]Demographic factors may have played an important role. Historians are not very informative on this aspect, but it is suggested almost as an evidence by Machiavelli (1469–1527), the Italian statesman and historian who lived in a time when the remembrance of Tamerlane (1370–1405) was probably still alive. In 1517 he wrote in his *Discourses on Livy*: "The other kind of war is when an entire people with all their families goes to seek a new seat in a new province. These people go out from their countries driven by necessity; and the necessity arises from famine, or war, and oppression, which in their own country is

sense that any battle won by the new leader strengthened and broadened his force of attraction and brought clans closer together. The physical analog would consist of following an isotherm on a (volume per mole, pressure) phase transition diagram; as one moves from the region of high volume per mole (i.e., low density) to lower volume per mole, one first sees some droplets of liquid form, and then progressively, an ever larger proportion of gas becomes liquid until eventually all the gas is liquid. If this mechanism is correct, it means that the episodes of territorial conquest experienced by the nomadic tribes of Central Asia have been triggered by a major population increase.

What was the threshold density of population, in other words what is the upper density limit of nomadic people living on their livestock and occasional hunting. This is certainly an important parameter and in order to find its order of magnitude the most reliable procedure is probably to look at the present day population density in regions where this mode of subsistence is still in effect. The following figures are for 1994: (i) the density of the vast area which comprises the Republic of Mongolia, Inner Mongolia (part of China) and Buryatia (a part of historical Mongolia now located in Russia) was 8.4 inhabitants per square kilometer; (ii) the density of Xinjiang in western China was 9.7; (iii) the density of the Chinese province of Qinhai which is located between Xinjiang and Tibet was 6.5. In all these cases the density of the grazing livestock was between two and three times the human density. To sum up, one can conclude that the upper density limit was around 8 people per square kilometer with about 2.5 head of livestock for each person. It should be noted that this limit is an upper bound but that the actual critical population density may have been somewhat lower. Once more population data about the previous historical episodes become available, it will be possible to say if our conjecture that they were driven by a common mechanism is indeed confirmed.

6. Multicomponent solutions and the melting pot mechanism

The integration of new immigrants is easier in large cities than in rural towns. Why? It is of course easy to provide a number of "anthropological" reasons such as better economic opportunities or the fact that the inhabitants of large cities are more used to the presence of various immigrants than the people in rural towns. Here we want to see whether our parallel with solutions can tell us something about this question. Two observations can be made in this respect.

- Roughly speaking, solubility requires that the molecules of the solute come in between the molecules of the solvent and that new links are established between the former and the latter. For this to occur the interactions between solvent

(*footnote continued*)
experienced by them. These people are almost all from the country of Scythia, a cold and poor place, where, because there were a great number of men and the country of a kind which was unable to feed them, they are forced to go out, having many things which drive them out and none to retain them" (adapted from the English translation of 1675, http://www.constitution.org/mac/disclivy_.htm, [48]).

molecules should not be too strong whereas the solvent–solute interactions should be as strong as possible. Translated into sociological language, the fact that integration is easier in cities means that the interactions in cities (solvent) are weaker than in towns or that immigrant–city interactions are greater than immigrant–town interactions (both conditions can be fulfilled simultaneously). Intuitively, these conditions seem to agree with common sense, but once again we are hampered by our inability to *measure* the strength of interactions.

- The previous discussion is not completely realistic because it considers a binary solution whereas in social situations there are several components. Although physical data handbooks contain less information about multicomponent solutions than about binary solutions, one aspect appears very clearly: multicomponent solutions are less selective than binary components. What do we mean by the expression "less selective"? The curves of the heat of mixing (as a function of alcohol concentration) for water–alcohol resemble resonance curves (see Ref. [40] or [41]). The fact that there is a sharp fall on both sides shows that energetically the solvation is less favorable as soon as one leaves the peak region; in other words the solubility is fairly selective. In contrast, for a multicomponent solution the heat of mixing curves are almost flat which shows that the solvation has a low selectivity. Intuitively, this is easy to understand for if the solution already comprises various molecules characterized by different kinds of bonds, it will be easy for any new molecule to link itself to one of them. This property of multicomponent solutions is illustrated in a more quantitative way in Table 4.

The more components there are, the less changes in the molar proportion of one of the components perturbs the solution, as reflected in the fact that the heat of mixing becomes almost independent of the proportion.

A qualification is in order at this point. Needless to say, we do not propose to take multicomponent solutions as a model of urban populations. That would be absurd. However, such systems provide true examples of collective phenomena involving several species of "agents" which can provide some insight into non-trivial forms of

Table 4
Relative selectivity of solvation according to number of components

	2 components	3 components	5 components
Coeff. of var. of Q/Coeff. of var. of proportion	77%	24%	12%

Note: The table tells us that a solution with several components is less "selective" than a binary solution. The percentages give the ratio of the coefficient of variation (i.e. standard deviation divided by mean) of the heats of mixing, Q, relative to the coefficient of variation of changes in the proportion of one of the components. As an illustration, for water + ethanol the ratio is equal to 0.98. The 2-component figure is an average over three cases: water + methanol, water + ethanol, ethanol + toluene; the 3-component figure is the average of the two following cases: benzene + cyclohexane + hexane (proportion changes refer to hexane), benzene + cyclohexane + *n*-heptane (proportion changes refer to heptane); the 5-component case is: benzene + hexane + toluene + cyclohexane + heptane (proportion changes refer to heptane).
Source: Landolt-Börnstein [41, pp. 536–540].

collective behavior. Our intuitive understanding of collective motions is fairly poor[5] and any means which can improve it should be considered of value. Simulations are one possible way to improve that understanding. However, it would be useless to set simulation rules without any guide. Multicomponent solutions provide real world examples of collective motion which can provide possible guidelines and help us to develop more realistic perceptions.

7. Conclusion

Although I have not proposed any model (time is not yet ripe for this) I hope this paper will help us to see a number of socio-economic phenomena in a more unified and less anthropocentric way. The potential usefulness of the parallels developed in this paper is that it gives us the incentive to compare phenomena which at first sight seem to have little in common. In this concluding section I would firstly like to discuss the question of ergodicity, an important theoretical issue on which depends the applicability of statistical mechanics, and secondly to suggest an agenda for future research.

7.1. Does the ergodicity hypothesis hold for socio-economic systems?

The success of statistical mechanics is entirely based on the fact that ensemble averages can be identified with time averages. On the theoretical side we compute the most probable configurations of the system on the basis of a collection of similar systems characterized by the same initial conditions and macroscopic constraints. A classical example is gas in a container in a state of equilibrium. Strictly speaking, the probability of finding all the molecules in one half of the container is not null, but it is overwhelmingly smaller than the probability of the situations where the molecules are uniformly distributed (except for small random fluctuations). The assumption that the time the system under observation spends in each macrostate is proportional to the probability of this state is of practical usefulness only if the system randomly explores all accessible microstates "quickly enough". As we have seen, for molecules in a gas or in a liquid the typical duration of a given configuration is of the order of one picosecond which means that within the time it takes to make a measurement the system explores over 10^{12} configurations.

No matter how we define the configuration space, it is obvious that it will be explored much more slowly in the case of socio-economic systems. For instance, on stock markets, probably one of the economic systems with the highest transition

[5]As an illustration consider the famed Schelling model [42,43] for spatial segregation. In this model, pennies and dimes are placed on a chess board and moved around according to specific rules. The board is interpreted as a city and the pennies and dimes as its inhabitants. Unfortunately, the rules are so rudimentary that it is impossible to connect them to real world data. As a result, the simulation does not allow any prediction and can, therefore, never be tested. Its main achievement is to show that segregation can be produced through simulation, a result which may have been of interest in the early days of simulation but which will not surprise anybody 30 years later.

rate, there is on average less than 10 transactions per second even for the most heavily traded stocks. For the other socio-economic systems the number of transitions may be smaller by several orders of magnitude. This has at least two consequences. (i) The time it may take for equilibrium to be reached may be large compared to the time scale of human observation. (ii) Consequently, there is a substantial probability of seeing the system in some metastable state rather than in its "true" equilibrium state. As a matter of fact, this problem is not specific to social systems; it also exists for some physical systems such as selenium, sulfur or tin which have different allotropic forms. For instance the transition from white tin to gray tin is supposed to occur at 13 °C, but it may take centuries for a plate of white tin to decompose into gray tin even at temperatures as low as −18 °C ([44] http://www.natmus.dk). Most of the tools developed in statistical mechanics are not well suited to such systems.

7.2. *Weak links, strong links*

Over the past decade, in the wake of the Internet revolution a vast literature has developed which is concerned with the structure of networks. However, its objectives and fields of applicability are altogether different from those considered in the present paper. Network theory is of relevance when there is a finite and well-defined set of links; this is often the case in cultural fields such as the network of cross-references in academic journals. On the contrary, the set of interactions of a given individual with the rest of society is neither countable nor well-defined. In such cases, trying to enumerate *all* links would lead nowhere. Consider the following example. Within a community, households interact indirectly with one another through the classmates their children have at school. Is this a weak or a strong link? In a sense it is weak because it is fairly indirect; however, we also know that it is strong enough to make families move to another area when for some reason the population of classmates becomes unsatisfactory. In order to test the strength of this kind of link one needs an operational definition; for instance, by measuring the relocation effects of a change in school population one would get a strength estimate. On this basis the link will be called a strong one, if a shift in school population makes many families move away.

In physics one is in a very similar situation. All atoms have gravitational interactions with all other atoms in the universe. Yet, for many phenomena those gravitation networks are of no relevance. What really matters is the strength of a given set of interactions relative to other sets. Thus, the network of gravitational interactions becomes important only when no stronger fields (for instance due to electric forces) are present. In short, the geometry of a network and its strength are two very different issues.

7.3. *An agenda for future research: gauging interaction strengths*

One may wonder whether the three manifestations of suicide that we examined can be accounted for by the same mechanism, in spite of the fact, that they correspond to very different time scales ranging from a few hours to several decades. To try to build a model at this point would probably be premature. If the model "explains" observed suicide rates in terms of social bonds that we cannot estimate in an independent way, this would be no more than a form of circular reasoning. This shows that one of our most urgent tasks is to develop methods for estimating the strength of social interaction. That this objective has so far been largely ignored by sociologists may seem surprising. How, for instance, is it possible to understand revolutions which basically consist in a rearrangement of social networks, if one has no real means for assessing the strength of social ties?

What methods can we think of for that purpose? There are two very different approaches. The one which is favored by most sociologists (if one excepts a few outsiders such as Stanley Milgram) consists in listing and studying different channels of interactions: family ties, neighborhood links, institutional connections, etc. This approach could seem fairly natural because it appeals to our intuition. We already know how family ties work (or so we think). However, that approach will not lead us very far. The variety of links is just too vast. In physics, we encounter the same difficulty when we try to look into the details of the interactions between molecules (in addition, keep in mind that molecular assemblages change every picosecond).

The physical methods for measuring the strength of molecular bonds suggest a completely different route. Whether we consider infrared spectroscopy, ultrasonic spectrography or X-ray/neutron scattering, these techniques are similar in their principle. A wave is sent through the medium and the ways in which it is affected are recorded and used to measure various characteristics of the medium. Through such measurements, one gets global estimates without having to worry about the minute details of the interactions. Infrared spectroscopy is slightly different from the two other techniques in the sense that it relies on the absorption which occurs when the frequency of the source coincides with the stretching or vibration modes of the molecular structure. So far, we do not know much about the eigenfrequencies (if any) of socio-economic systems which means that this technique does not provide a straightforward approach (at least for the time being). The two other techniques have broader applicability. For instance, in ultrasonic spectrography an ultrasonic wave is transmitted through the medium, its velocity and attenuation are recorded, and from these measurements one may derive many properties of the medium, for instance its density, the size of emulsion droplets or the existence of a temperature gradient.

If one wants to extend this kind of approach to the social sciences there is a crucial requirement. In order to be able to use light or sound waves as probes, one must already know how these signals are affected by the physical characteristics of the medium. In other words, it is only once we have gained some kind of understanding (even if it is only an empirical understanding) of how a given signal is affected by a society, that we can use it as a probe. Once this condition is fulfilled, this probe will then become a useful tool for further explorations in a kind of cumulative process where any new knowledge about social interactions is used as a springboard for additional discoveries.

There are many social signals which should enable us to transpose the previous approach to the social sciences. For instance, the way an epidemic propagates in a society can reveal a lot about the interactions that take place in a population. As an example, one can mention the fact that if two population groups show very different levels of prevalence for a sexually transmissible disease such as gonorrhea, chlamydia or HIV one can be almost sure that the two groups have little interactions through marriage or non-marital sexual contacts. Such assessments can be checked by confronting them against inter-marriage rates. Alternatively, they can replace such statistics in countries which, for some reason, do not record this kind of data. Naturally, this example concerns only one particular aspect of social interaction. One would have to develop similar approaches for other aspects as well. The transmission of rumors, innovations or new fashions can provide other possible probes.

In this paper, I tried to convince the reader of the key role of interaction strength in social phenomena. I am convinced that once we get a clearer picture of this factor many socio-economic phenomena will become more transparent and to some extent more predictable.

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