Part I

Bridging the gap between physics and the social sciences

The emergence of two new fields, the science of chaos and the science of networks, has changed the way in which we look at physical and social systems. From the first we learned that simple (in the sense of having few degrees of freedom) physical systems can undergo chaotic motions and display intricate trajectories. The double pendulum is one of the simplest systems of this kind. Initiated by Benoît Mandelbrot (1975) and Robert May (1976), the science of chaotic systems and fractals has already produced substantial achievements. This book relies only occasionally on the analysis of chaos; in contrast it relies heavily on the ideas of network science. Although it can be traced back to system theory which flourished in the 1960s and 1970s, network science really emerged in the late 1990s through the works of people such as Albert-László Barabási (2002), Sergei Maslov (2002), Steven Strogatz (2003) or Duncan Watts (2003). It has been instrumental in convincing us that what really matters in a system is its nodes, its links and their respective weights. Seen in this perspective, the real nature of the system, whether of physical, biological or social nature, is of little relevance.

But looking at physical and social systems in an abstract, purely structural way takes away much of their substance. The real challenge is to do real physics and real sociology in the framework of network theory. This is what we call "bridging the gap". In the five chapters which compose this first part we analyze the implications of a perspective based on network science without losing contact with real systems. We consider the problems of measuring the strength of bonds, of reducing the level of noise in social systems; we discuss the differences between equilibrium and non-equilibrium phenomena. Finally, by way of specific examples, we emphasize that the question of data reliability has so far received too little attention in the social sciences.

1

Probing bonds

The fact that interactions and bonds play an essential role in physical phenomena can hardly be disputed. Their role in the social world is no less important. The parallel between these two classes of phenomena can be illustrated by two key episodes: the formation of stars and the emergence of agrarian-based societies.

- In the early universe there were molecular clouds composed of low density hydrogen and helium gas. According to current conceptions of star formation, regions where density was high enough (as a result of random fluctuations) became gravitationally unstable and began to collapse. The gravitational collapse released a lot of heat and energy in the same way as a stretched spring releases its potential energy as it resumes its equilibrium length. Part of the energy was radiated but the remainder increased the temperature of the core until fusion ignition occurred. This marked the birth of a new star. If its mass was greater than five solar masses it had a fairly short life time. After several million years its core began to contract and as it shrank it grew hotter; this triggered a new series of nuclear reactions leading to the formation of heavier elements up to iron. Eventually, through a mechanism which is not yet clearly understood, the star exploded. It is known that elements heavier than iron were formed during this supernova explosion. Through its disintegration, all elements contained in the star were released into space to serve as raw material for new stars, planets and living creatures.
- The neolithic revolution occurred only about ten thousand years ago but its successive steps are not so well known as those in the evolution of stars. Before the neolithic revolution there were low density populations living a largely nomadic life based on hunting and gathering. For some reason, a higher than average density of population developed in some places, therefore limiting the territory available to nomadism. Gradually permanent or semi-permanent settlements appeared, and gathering techniques became more intensive, eventually leading to crop cultivation. As the improved techniques could sustain more important population densities, population concentration continued, leading to the formation of towns and cities and to the emergence of techniques which represent important landmarks in the evolution of mankind: storing grains, making pottery, developing written languages, and introducing political and religious forms of social organization. The first cities may have lasted a couple of centuries but eventually

wars, diseases or internal factors made them crumble and collapse. While some of the newly developed techniques may have been lost, it seems reasonable to assume that most of them were disseminated and recycled in new settlements.

In short, from a network perspective, the two scenarios comprised the following steps. (i) Contraction brings about more interactions. (ii) Greater interaction leads to the formation of more complex entities. (iii) Disintegration eventually produces a spatial dissemination of the new entities. (iv) These new entities are reused as building blocks in subsequent processes. If this parallel does not appear completely convincing it is probably due to the following reason. Whereas we are familiar with the concepts of gravitational and nuclear attractions which account for the evolution of stars, we have no specific concepts for characterizing and differentiating the interactions in a society of hunters on the one hand and in an urban society on the other hand. Of course, we can explain and outline the differences but we have no means for describing them quantitatively. For a society there are no notions of temperature, heat, energy or entropy. We do not know how to characterize the interactions between wheat farmers, soldiers and priests in Ancient Egypt for instance.

In the same line of thought it is tempting, especially for a physicist, to mention a third kind of episode, namely cultural and scientific revolutions. Among several possible cases, we select the birth of quantum mechanics in 1925–8. We will see that it is not unlike the birth and explosion of a hot supergiant star. In the previous three decades, a wealth of experimental results had been produced which had received no consistent and comprehensive explanation. One can mention for instance the discovery of radioactivity, the emission spectra of atoms, the emission of α-particles by nuclei, the absorption coefficients of X-rays, the extraction of electrons from a metal by an electric field, and so on. In spite of a number of scattered phenomenological attempts there was still no comprehensive theory in the early 1920s. Then, within a few years, not one but several frameworks were proposed which eventually proved to be equivalent. One may wonder what was the role of social networks in this revolution.

As the group of physicists engaged in the exploration of the atomic world was a small community they often met and knew one another fairly well; thus there were links between Niels Bohr, Albert Einstein, Max Planck and Ernest Rutherford, to mention just a few of them. This community had a crucial function as a scientific filter in the sense that new theories were discussed, tested against evidence from new experiments, and (most often) were found wanting. This was a kind of potential barrier which prevented the adoption of unsatisfactory, makeshift theories. That was the normal mode of operation of the system, but between 1925 and 1928 it worked with much greater speed and efficiency. Berlin, Cambridge, Copenhagen, Göttingen, Leiden and Munich had for years been magnets attracting young talent; after 1925 it seems that Göttingen became the center of this network. Is it not revealing that in 1926–7 Arthur Compton, Paul Dirac, Linus Pauling, John von Neuman, Robert Oppenheimer, Edward Teller and Eugene Wigner, none of whom was German, visited Göttingen, staying there for several weeks or months and meeting one another (Rival 1995)? They were young and were not the main actors in this revolution, but they took part in it. The new ideas were actively discussed during many informal gatherings either at Max Born's home or at one of the inviting inns that could be found in the countryside surrounding Göttingen. In 1928, when the supernova exploded, the Göttingen researchers were scattered far and wide. In subsequent years, they would apply the new theoretical tools they had mastered to various subjects from chemistry to nuclear physics, astrophysics and several other fields.

Many other episodes similar to the quantum revolution can be found in the history of science. The process seems to be always the same. (i) Accumulation of precise and unexplained experimental results. (ii) This body of evidence acts as a converging lens through which the efforts of many researchers become focused on the same objective. (iii) This concentration of efforts eventually leads to a new theoretical framework. The revolution occurs in a place where the concentration process has been particularly intense but often another (more or less equivalent) solution is proposed almost simultaneously by another group of researchers. (iv) After the breakthrough the new tools are exported to other fields where they are employed with success. Describing these mechanisms quantitatively appears even more difficult than for the neolithic revolution. Nonetheless, it is possible to define objective criteria; for instance, a possible way of describing the links between different groups of physicists would be to use the academic genealogy method introduced by Sooyoung Chang (2003), an approach which is based on the links between thesis advisers and their graduate students.

In this chapter and indeed in the whole book we will try to develop a number of tools which can help us to measure social interactions. In order to be in the most favorable position we will mostly focus on phenomena for which vast statistical databases are available; this is for instance the case for commodity markets, suicide rates or international relations. Because in physics we have elaborate knowledge of how to measure bonds and interactions, it is natural to use those parts of this knowledge which can be useful for our purpose.

The present chapter is organized as follows. First, as a case in point, we describe in some detail the experiment which led Rutherford to the discovery of the nucleus. Apart from its historical importance, this example will show how important it is that the probe (in this case α-particles) is well adapted to the size of the entities that one wants to identify. After this example, we list and describe other means that can be used to gauge interactions. Finally, in the last section we briefly review some methods such as correlation analysis which are already used in the social sciences; we explain why they are not satisfactory for the purpose of measuring interactions and we examine how they can be improved.

1.1 The Rutherford experiment

The Rutherford experiment can be considered as a particularly successful illustration of a general strategy which can be summarized as follows. The system under consideration is subjected to a controlled exogenous change and from the way it responds to this change one tries to derive the form, range and strength of the interaction.

In many descriptions of the Rutherford experiment it is claimed that its main novelty and achievement was the fact that some of the incident particles were scattered backwards. In fact, experiments in which the incident particles were highly deflected to the point of re-emerging from the same side of the target had been performed several years before the Rutherford experiment. What was really new was that Rutherford and his collaborators had good reasons to think that in their experiment the reflected particles had experienced single (and not multiple) collisions. Their argument relied on the observation that most particles were little deflected; as a matter of fact, 99.990% of the particles experienced very small deflections. Thus, paradoxically, the particles which were not deflected were as important as those which bounced backward. After a short description of the experiment we explain why its interpretation was by no means straightforward. Finally, we discuss possible implications for our topic.

As we know, Rutherford used α-particles to explore the structure of gold atoms. It is important to realize that several other probes were available at the time, particularly cathode rays, X-rays and β-rays.[1] Table 1.1 shows that the α-particles were the only probe capable of exploring the nucleus. The wavelengths of the other probes were too large. Before discussing further implications let us describe the experiment. The α-particles were directed normally onto a very thin sheet of gold (Fig. 1.1). A fluorescent screen (made up of zinc sulfide) which produced tiny flashes of light when hit by α-particles was used to detect the scattered particles. The number of scintillations per minute and per square millimeter of the screen was counted by means of a low power microscope. There were three kinds of trajectories. (i) A fraction of the α-particles was absorbed by

[1] Let us recall the definitions of these expressions in modern terms. Cathode rays are streams of energetic electrons, X-rays are energetic electromagnetic waves, β^- rays are streams of electrons, β^+ are streams of positrons. α-rays are helium nuclei composed of two protons and two neutrons. At the end of the nineteenth century the word "rays" was used in a fairly vague way because the exact nature of these rays was unknown. In modern terminology, the term "ray" has been kept only for X-rays which are indeed a form of light radiation.

Table 1.1 *Probes available around 1909 for exploring the structure of the atom*

Name of probe	Nature of probe	Charge	Wavelength (10^{-14} meter)
Cathode rays	electrons	−	1,000
X-rays	photons	0	1,000
β-rays	electrons	−	10
	or positrons	+	
α-rays	2 protons	++	0.1
	+ 2 neutrons		

Notes: The diameter of a gold nucleus is about $d = 10^{-14}$ meter. Only probes with a wavelength shorter than d will be able to detect the nucleus. This criterion generalizes the rule well known in optics which says that, whatever its magnification power, a microscope will not permit the observation of details smaller than the wavelength of visible light (i.e. 4×10^{-6} m). The wavelength of cathode rays is determined by the voltage between cathode and anode; to get an order of magnitude we consider the wavelength of modern electron microscopes. The energies of the β- and α-rays available at the time were of the same order of magnitude, about a few Mev. For a particle of kinetic energy E whose velocity v is less than 40% of the speed of light, one can apply the following non-relativistic formulas (the difference with respect to relativistic formulas is less than 10%): $v = \sqrt{2E/m}$, $\lambda = 2h/mv = h\sqrt{2/Em}$ where h is Planck's constant, m the mass of the particle, and λ its associated wavelength. As the mass of an α-particle is about 8,000 times the mass of an electron, its wavelength will be $\sqrt{8{,}000} \sim 90$ times smaller than the wavelength of a β-particle of same energy.

the target. (ii) Another fraction was transmitted through the gold sheet without being substantially deviated. (iii) A small fraction (about 0.01%) of the scattered particles experienced a deflection of more than 90 degrees which means that they emerged from the same side of the plate as that on which they hit the target. The fact that scattering of more than 90 degrees had already been observed for β-particles is clearly stated at the beginning of the paper by Geiger and Marsden (1909) who were Rutherford's collaborators: "When β-particles fall on a plate they are scattered inside the material to such an extent that they emerge again at the same side of the plate. For α-particles, a similar effect has not previously been observed." What made the reflections of the α-particles important was the fact that they were rare, for this suggested that they were not caused by multiple scattering as was presumably the case for the β-particles. This was a crucial point, for one must remember that even the thin gold foil used in the experiment had a thickness of about 2,000 atom diameters. With only one α-particle in 10,000

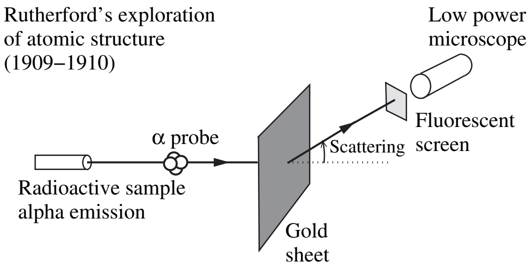

Fig. 1.1 Schematic representation of the Rutherford experiment. The α-particles consisted of helium nuclei composed of two protons and two neutrons. Although the gold foil constituting the target was as thin as possible it nevertheless had a thickness of about 2,000 times the diameter of an atom. Therefore the question of whether or not the α-particles experienced multiple scattering was a crucial issue. Large scattering angles had already been observed in earlier experiments, in particular with β-particles, but they were attributed to multiple scattering. So what made the Rutherford experiment remarkable was not the fact that large scattering angles were observed but rather the fact that the cross section of the α-particles was small enough to exclude multiple scattering.

being diffracted there was indeed a good chance that no multiple scattering had occurred. In short, instead of producing multiple scatterings which were difficult to interpret, this experiment produced much "cleaner" results. It is in this sense that the Rutherford experiment was a prefiguration of the accelerator experiments which were carried out in subsequent decades. The three elements of an accelerator experiment were already there, namely (i) a source emitting an energetic stream of particles, (ii) a target and (iii) a detector allowing measurement of the scattering angle.

What are the implications of the Rutherford experiment for the design of quasi-experiments in the social sciences? First of all, its success was ensured by selecting the "right" probe. Because α-particles were positively charged they were repelled by the gold nuclei and because they were sufficiently energetic they were able to probe the tiny nucleus.[2] This statement is easy to make with the wisdom of hindsight, but in 1909 it was not immediately obvious that the observation could not be interpreted in the framework of the prevailing plum pudding model. After all, even in this model the charge of the atom was concentrated in the plums and was not distributed uniformly. As a matter of fact, it was only two years after the experiment that Rutherford proposed a model in which the positive charge was concentrated in only one plum, the nucleus of the atom (Rutherford 1911). One should keep in mind that Geiger, Marsden and Rutherford carried out similar

[2] The Rutherford experiment did not yield any insight into the electron cloud which was of course known to exist to make the atom electrically neutral. For that purpose the energy of the probes was just too high.

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measurements with other metallic targets: aluminum, copper, iron, lead, platinum. Moreover, after its results had been published the Rutherford experiment was repeated by several other groups. Not only were its observations confirmed but they were also tested in a broad range of experimental conditions. In spite of the novelty of the Rutherford experiment, one should not expect a real breakthrough to result from a single experiment; it was rather one link, albeit a crucial one, in a long chain of experiments. Cathode rays, X-rays, β- and α-particles all contributed to progressively shape and sharpen the picture. These efforts were productive and fructuous because they were focused on a single, well-defined question: what is the structure of the atom and what are the interactions between its different components? In contrast, in the social sciences, investigations are scattered over a broad range of questions. As a result the process of accumulation of knowledge and understanding works very poorly. It is one of the main objectives of this book to show that bonds and interactions between social agents play a key role and therefore deserve extensive investigation. This objective can provide a unified purpose and framework for various contributions and thus start a process in which knowledge can be produced in a cumulative way, as is the case in physics.

As far as the methodology of the Rutherford experiment is concerned it can be adapted to the social sciences without much difficulty, at least in its principle. Any shock, modification or mutation can be used as an experimental probe. However, it is much more difficult to define a set of *calibrated probes*, by which we mean a set of shocks whose intensity and duration can be controlled. In a subsequent chapter, the attack of September 11, 2001 will be considered as a probe and we examine how suicide rates responded to this event. It will be seen that September 11 had no measurable impact on suicide rates in the United States.[3] In short, big events such as September 11 do not provide good probes for the phenomenon of suicide. But big events can be used as probes for other phenomena. For instance, the destruction of the Ayodhya mosque in northern India in December 1992 brought about considerable disturbances between Hindu and Muslim communities in countries as diverse as Afghanistan, Britain, Canada and Pakistan.[4] This suggests that events of this kind are good probes for investigating the interaction between religious communities. However, even in this case we do not have a set of calibrated events, but rather we have a small number of events whose intensities can only be estimated on a fairly qualitative basis. We come back to this question in the next chapter.

[3] In a sense this absence of impact is similar to what is observed in the Rutherford experiment at the level of 99.990% of the particles which go through the target without being deflected. Unfortunately, in the case of suicides the accuracy of the measurement is too poor to identify a possible effect as small as the 0.01% deflected particles in the Rutherford experiment.

[4] For more details see Roehner (2004, Chapter 4) or Roehner, Sornette and Anderson (2004).

It must be emphasized that test-probes do not need to be shocks but can also take the form of structural changes. In the next section we give a number of examples of test-probes of this kind.

1.2 Boiling points as test-probes

In sociological language, evaporation and boiling can be seen as a drop-out phenomenon. When a molecule which is close to the surface of the liquid has enough kinetic energy (as a result of thermal agitation) it can overcome the attraction of surrounding molecules and escape from the liquid. When the process occurs at temperatures below the boiling point it is the phenomenon of evaporation. At boiling temperature the drop-out phenomenon spreads from the vicinity of the surface to the bulk of the liquid. Thus one expects the boiling temperature to have a strong connection with the strength of intermolecular interactions: the stronger the interaction, the higher the boiling point. This relationship is illustrated in Fig. 1.2a. It can be seen that for alkanes the boiling temperature increases along with molecular weight. For alkanes there is a direct relationship between molecular weight and intermolecular interaction (see Fig. 1.2b). However, this is not true

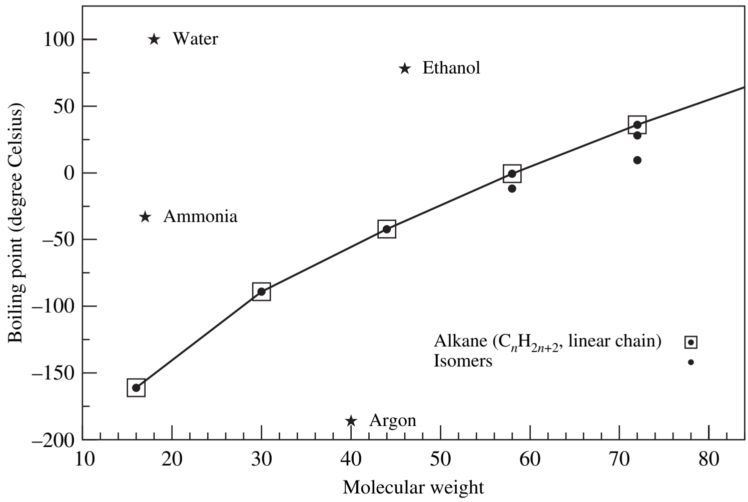

Fig. 1.2a Boiling point as a function of molecular weight. It is fairly easy to explain why the boiling point is connected with the strength of the molecular attraction, but it is far more difficult to explain this attraction in terms of the characteristics of the molecules. For alkanes, molecular attraction happens to be proportional to molecular weight (see Fig. 1.2b), but this rule holds only for alkanes. Even for their isomers (i.e. those alkanes which do not have a linear chain) the rule is only roughly true and it is not true at all for the substances indicated by stars. *Source: Lide (2001).*