2 Vision and modelling of complexity

THE PARADIGM OF COMPLEXITY offers a universal vision of how the world works. To do so, it adopts as a fundamental premise the decentralised character of natural and social systems. In these systems, the continuous interaction of agents at a certain level of analysis (e.g., cells, species, companies and political parties), gives rise to properties and patterns at another level (e.g., organisms, ecosystems, economic cycles and electoral tendencies, respectively). In the social sphere, two examples of these emerging patterns, or statistical regularities, are the sudden collapses that occur in asset prices, and the segregation of individuals in cities based on their level of income, ethnicity or religion.

The vision of complexity provides an alternative perspective which, in many circumstances, enables the formulation of evidence-based public policies and better informed business strategies. Through this lens, it is possible to understand why vehicle mobility can improve when it is the traffic that drives light changes at traffic lights and not vice versa, as is the current practice; why the 'brainstorming' that takes place at boards of directors and in planning committees is not always fruitful; why industrial policy makes a lot of sense when it promotes the development of productive capabilities and encourages the exploration of opportunities, but not when it is based on politicians or technocrats 'picking winners'.

This book contextualises the paradigm of complexity within the socioeconomic field. To this end, the "science of social complexity" is framed within this universal perspective, but is conceived from a meta-theory about human behaviour and the latter's socio-cultural structure. It should be noted that the use of a meta-theory is essential for the formulation of particular theories based on rigorous analyses. Once the meta-theory has been defined, researchers can elaborate hypotheses on specific topics limited to the historical specificity of a certain time and space. This science is of a computational nature, given that algorithmic procedures enable a simulation of the way in which social, economic and political phenomena are generated with agents who act in a decentralised fashion.

Like other computational approaches of the social sciences, the theories of social complexity originate in the conceptualisation of societies as information processing systems [Cioffi-Revilla, 2017]. As such, the computational approach to social complexity can be used in a two-fold manner: (1) as a simulation tool and (2) as a theoretical framework for describing complex, adaptive systems. Attempting to understand the way in which social agents acting at different scales (i.e., individuals and collectivities) process information (i.e., act based on data) is fundamental to explaining social dynamics and how a society becomes complex. From an epistemological perspective, computing is an ideal tool for modelling and studying the complexity inherent in social phenomena. The history of the development of science shows that great advances have been made possible thanks to the use of new concepts, theories and data, but also due to the adoption of innovative scientific instruments (e.g., the telescope, microscope, mathematics). Based on the latter, it can be affirmed that the use of computers will allow the formation of new ways of observation and methods of analysis in the coming years.

Chapter aims

One of the aims of this chapter is to present the vision of complexity as a form of describing reality, in which decentralised processes favour the self-organisation of macroscopic behaviours, in addition to explaining the fundamental premises of this vision and contrasting them with the orthodox economic paradigm. Using examples drawn from the natural and social environments, the chapter demonstrates the virtues of using simulations of artificial worlds to illustrate the vision of complexity and carry out experiments that help to identify causal mechanisms. Rather than presenting computational models that describe real phenomena of different kinds in detail, the chapter employs simple simulations to explain the concepts and explore arguments.

Chapter structure

The chapter is structured as follows. The first section presents the decentralised vision of complex systems, which is contrasted with the neoclassical conception of economies. The second section proposes that the fundamental premises of complex adaptive systems make this vision fitting for the study of socioeconomic phenomena. In addition, it addresses the imperative of developing a meta-theory to adapt the paradigm of complexity to the social sphere. In the third section, the concept of the 'self-organisation of collective behaviour' is defined, and the differences between complex systems and those that are simple or complicated are described. In the fourth section, simulations of the natural world are used to exemplify the relevance of decentralised processes in the explanation of collective behaviours.

Using simple problems of vehicular traffic, the fifth section shows that modelling by means of artificial worlds is very appropriate to understanding social behaviours and designing public policies. The sixth section expounds upon one of the classic models of social complexity: the model of social segregation, which exemplifies the advantages offered by computer models for analysing ideas and presenting arguments. In the seventh section, certain key features of models simulating the mass movements of people in public spaces are reviewed. These models aim to illustrate how collective behaviours of a social nature can be explained by simple rules (heuristics) of human behaviour, instead of appealing to rational behaviours that presuppose sophisticated information processing.

2.1 Decentralised processes

The fact that theories of complexity emphasise the relevance of decentralised processes does not mean that all the agents of a system impact the observed macroscopic regularities in the same way. The decentralisation of these systems has to do with the interaction of a multiplicity of agents with potentially very diverse behaviours. For example, the power relationships within a society do not prevent conceiving the distribution of income as a result that emerges from a system of this nature. Likewise, the presence of absolutist monarchies and dictatorships does not rule out that historical processes and the construction of formal and informal institutions are the product of the interactions between agents and their mechanisms of adaptation to the environment.

At the end of the 20th century, the world experienced decentralising movements that emerged in different socioeconomic arenas. Due to this, it is today much easier to understand the relevance of social processes that are generated from below. For this reason, many researchers' interest in interpreting social phenomena through the lens of complexity has been reinforced over the past few decades [e.g., Helbing, 2013]. The fragmentation of the Soviet Union and the transition from communist societies to market economies are examples of these processes. Further examples include the fall of dictators and single parties, replaced by democratic regimes in a large number of societies, and the renewed vigour of civil society based on the creation of non-governmental organisations with very diverse agendas.

In the same way, this vision is justified by the emergence of the following processes: the restructuring of large hierarchical companies through affiliates or relatively autonomous subsidiaries; the establishment of strategic alliances or flexible business networks; the demolishing of state control over the media within each country due to the adoption of cable TV systems, satellite transmission and the propagation of news through the Internet and social media; the outbreak of nationalist and regionalist tendencies that have revealed themselves before established authorities and the onslaught of globalisation; the appearance of terrorist cells that are organised around the world without apparent central control; the dynamism of computer based social networks – such as Twitter and Facebook – in disseminating news, spreading rumours, establishing topics of debate and mobilising civil society.

In spite of this clear tendency in the contemporary world, Resnick (1997) maintains that the human being interprets his/her environment with a centralist mental scheme. In the field of academia, this vision is not innocuous, since it affects the way in which a large number of researchers explain social and natural phenomena. In other words, theories are formulated from the glass lens through which the world is perceived. For this reason, in ancient times, the earth or the sun was seen as the centre of the universe. There are even historians and political scientists who suggest that the performance of nations is determined exclusively by the ability or caprice of their leaders.

Today, it is common to find points of view indicating that a country's future is at the mercy of whoever is elected as president, or that a company's potential depends only on its majority shareholder or chief executive officer. This same centralist propensity explains why conspiracy theories are easily propagated, which attribute a society's political and economic events to a small number of individuals, or why the public in general – and some academics – assign the misfortune of economically backward countries to the designs of the powers 'controlling' the international economic order.

The decentralised vision of economics

Without seeking to undermine the role undoubtedly played by hierarchies and power relationships within socioeconomic systems, social theories must adopt a decentralised vision of the phenomena to be analysed. Classical eighteenth-century economists, such as Adam Smith, with his emphasis on the specialisation of labour, and Thomas Malthus with his analysis of population growth in an environment of food scarcity, created the cornerstones for elaborating theories based on a decentralised perspective. A clear example is the so-called 'invisible hand' of the markets which, under certain conditions, leads to the efficient allocation of resources – a phenomenon that occurs without the intention of individual producers. However, the classical conceptualisation lost its original perspective following the reformulation of Walras in the nineteenth century. In describing market price determination with a set of algebraic equations, Walras channelled a centralist view of economic science. Paradoxically, in books dealing with microeconomics, the works of this author are referenced as an analysis of a system of exchanges in 'decentralised markets'.

In neoclassical Walrasian economics, the only form of interaction between people occurs in the context of prices, which are established by means of a fictitious analytical apparatus of a centralised nature, known as a 'Walrasian auctioneer or *tâtonnement*' [Kirman, 2011b]. However, the absence of such an auctioneer in the real world prevents excess demand from disappearing immediately, since a rise in market prices does not occur in a coordinated manner. The mechanics by which prices are determined in reality, and the way in which agents form their expectations, are critical for reaching an equilibrium [Chen, 2016, Chap. 3]. In fact, the presence of the Walrasian auctioneer does not guarantee that the equilibrium would be stable for certain types of preferences [Kirman, 2011b].

The axioms that are used to prove the existence of a vector of equilibrium prices prevent the neoclassical theoretical apparatus from incorporating essential factors on human behaviour and the organisation of markets. These factors foster the recurrent disequilibria that are observed in reality. Unfortunately, the mathematical treatment behind existence theorems affected the later development of the discipline. The introduction of centralist assumptions in the demonstrations of these theorems, such as the presence of rational actors and exogenous preferences, set the tone for the construction of the methodological canons with which 'rigorous research' is carried out in the field of economics today.

Throughout the 20th century, a centralised definition of economics was consolidated, which conceptualised it as "the science which studies human behaviour as a relationship between ends and scarce means which have alternative uses" [Robbins, 1932, p. 15]. This definition, together with the premise of rational individuals, led to the analytical apparatus of economics being built by solving optimisation problems. This assumption reinforced the centralist treatment of the discipline, given that the need to optimise implies the existence of an entity that solves the problem of resource allocation, be it a producer, consumer, government or social planner. For example, this formulation brought about the interpretation of the company as a profit maximising, monolithic entity, and not as a social organisation composed of heterogeneous actors who interact based on particular rules. This approach also relegated the importance of structure and gave rise, in the field of macroeconomics, to the theoretical supremacy of microeconomic foundations based on conditions of equilibrium and a rational representative agent [Syll, 2016].

The scarcity of resources characterising the real world is not discarded under the perspective of complexity but is, rather, incorporated into the theory by assuming the existence of adaptation processes. In other words, agents (individuals and organisations) in the social world do not deal with the problem of resource allocation through a deductive optimisation analysis; they do so based on their ability to adapt. In this way, the agents interacting with each other and with their environment carry out modifications to their strategies, in addition to undertaking technological innovations and promoting institutional reforms. It should be remembered that, again and again, biological science has shown that nature has been very efficient in adapting to a number of environmental disturbances through evolutionary processes – changes that have, indisputably, been made in conditions of resource scarcity and without the presence of rational actors.

In fact, the adaptation of agents in social or biological environments can be interpreted as a 'population optimisation' scheme. In this sense, Beinhocker (2010) points out that the mechanism of evolution should be seen as a decentralised search algorithm:

its objective is to find instructions (attributes or designs) with the best possible performance in a space that is in continuous movement and that presents a large number of dimensions and variants. This collective optimisation mechanism generates very good results when dealing with computationally complicated problems (such as NP-hard or high-dimensionality). These types of problems cannot be solved in a deductive way; for their solution, algorithms are required that are capable of preventing processing time from increasing rapidly as the magnitude of the information increases.

The natural world works much better than the social world created by human beings because, in the former, there exist channels through which information flows in an agile manner. The response capacity of the natural world is due to the fact that molecules, cells and organisms communicate with one other to adapt to environmental vicissitudes. This situation has facilitated the 'bottom-up' self-organisation seen in the creation of organisms from cells, and in the development of a beautiful and complex flower from the compounds of a simple seed. In contrast, social systems, faced with deficiencies in the quality of information and the absence of adequate rules of interaction, have frequently resorted to top-down organisation – a scenario that, on repeated occasions, has given rise to dictatorial regimes, bureaucratic organisations and stagnant companies.

Nonetheless, the decentralising trend of the current world has given way to greater possibilities for interaction and a better flow of information, with the consequent reduction in coordination costs. By increasing the probability of finding solutions to problems of collective action, the presence of sophisticated socioeconomic systems becomes much more feasible. That being said, it should be clarified that not all processes of self-organisation are beneficial to social wellbeing: they can also engender the existence of terrorist networks, the propensity of markets to create and perpetuate the maldistribution of wealth, and the occasional stock market collapses with all the disruptive effects that these imply, among other negative phenomena.

2.2 The premises of an alternative paradigm

In order to understand how socioeconomic phenomena occur, it is useful to incorporate four main factors into the theoretical framework that influence individuals' decision making and aggregate behaviour: (1) social interaction, (2) heterogeneity, (3) uncertainty and (4) adaptation to the environment. Unlike the reductionist positions, in which the functioning of the whole is studied through the analysis of its parts, it is here stated that macroscopic behaviours are the result of individual decisions conditioned by a process of interaction; that is, by interdependent decisions between agents that exhibit some type of connectivity (e.g., geographical, organisational or social).

According to Granovetter (1985), individuals and their decisions are socially embedded, making it impossible to study agency without considering structure. For example, a society's consumption patterns can be explained, to a large extent, by preferences shaped by marketing, social pressure and conformity, and not by the exogenous preferences of atomised individuals, as supposed by neoclassical models. This same premise is also fundamental to the natural sciences: it is not possible to understand the temperature of a body without analysing the connectivity and interdependence between the molecules that compose it, or the functioning of an organ without being aware of how the different cells are linked.

Agents are heterogeneous for different reasons: endowments (economic and genetic), beliefs, preferences, psychological propensities, and location, among others. In addition, the diversity of agents is accentuated as a result of the interaction processes that take place at the local level. Hence, aggregate behaviour cannot be inferred from the sum of individual behaviours, contrary to what the neoclassical approach suggests. In the latter, the use of a representative agent causes the analyst to incur a 'fallacy of composition', in which the properties observed at a certain level of analysis are imputed to another level. As such, in economic orthodoxy, the phenomena to be explained are deduced by analysing the individual behaviours of socially isolated agents.

Taking into account agents' interaction and their heterogeneity is fundamental to being able to model and explain the way in which individual behaviours give rise to statistical regularities in the aggregate variables of interest. It should be added that the use of the representative agent is inconsistent with the empirical evidence [Stoker, 1993], and that this approach erroneously suggests that the preferences and optimal selections of the aggregate correspond to the preferences and optimal choices of the individual agents [Kirman, 1992].

In line with Frank Knight's (1921) position, socioeconomic agents make decisions in a context of uncertainty. This is due to the difficulty they have in evaluating the behaviour of others and estimating the probability with which there will appear contingencies that affect the environment. In this sense, the neoclassical premise of 'agents that maximise their expected utility' emerges as inappropriate in many circumstances. Bounded rationality not only hinders the choice of optimal behaviours but, in addition, implies that the individual is unaware of the distribution of the probability associated with critical environmental variables. From this perspective, Peters (1999) argues that risk is linked to the possibility of quantifying a potential loss, while uncertainty has to do with the unknown and with environmental vicissitudes.

It can, therefore, be stated that in a world containing risk, the probability of an event can be known, but the realisation of it taking place is unknown. On the other hand, fundamental uncertainty prevails in a Knightian world, where the nature of events and their probability are also unknown. Another, highly relevant form of uncertainty is that which characterises dynamic processes. In these, future scenarios are little known and are subject to constant innovations, such as those emanating from technological developments and institutional reforms. In other words, both fundamental and institutional uncertainties arise from the scant certainty that exists for anticipating individual and collective behaviours. For this reason, in a context of decentralised decisions, it is unreasonable to think that market prices will adjust promptly to a state of equilibrium in which buyers and sellers have no incentive to modify their behaviour.

Individuals do not have the information or cognitive abilities to know precisely how the world around them works, which is contrary to the assumptions of rational expectations models. However, their actions do tend to occur based on their preferences, and with the aim of solving the problems they face on a daily basis. The limited rationality that drives agents to decide based on levels of satisfaction [as in Simon, 1957], to react to certain stimuli, or to act in a conformist manner, makes it possible for them to respond to the circumstances that arise. The human being's capacity for adaptation in a context of endemic uncertainty makes it methodologically more convenient that socioeconomic phenomena be conceived as open problems, in which disequilibrium is more the rule than the exception.

In the neoclassical paradigm, individuals also respond to 'exogenous disturbances' in certain parameters (such as tastes, technologies and endowments), and their behaviour affects the environment in which they operate (e.g., through inflation, unemployment, inequality). However, in such an approach, modifications to the environment do not exert any renewed effect on individual behaviours once a point of stasis or equilibrium has been reached. By way of illustration, an analysis of equilibrium indicates that a more favourable expectation of the economy by entrepreneurs induces greater investment. This, in turn, validates the initial expectation, so that changes in entrepreneurial behaviour end up stopping. In contrast, it is said that agents' behaviour is coevolutionary when their actions – based on beliefs about the actions of others – generate a collective behaviour that transforms the environment, which leads to a new round of modifications. All of this occurs without necessarily reaching a fixed point in which the behaviour (C) that promotes change in the environment (E) manages to sustain itself (stasis: C → E → C versus coevolution: C → E → C'→ E'…).

The importance of a meta-theory

The so-called 'econophysicists' affirm that the future of the social sciences lies in recognising that human beings are part of nature. Hence, explanations of their collective behaviour should be devised according to a theoretical framework similar to that of other living beings, and even to that of inanimate objects. According to this position, progress in the natural sciences has been possible thanks to the detection of patterns in collective behaviour, and its explanation based on the interactions between the units that shape this behaviour (e.g., atoms, molecules, cells, species). Phenomena as diverse as the conduction of electricity, magnetism and the formation of liquid crystals are the result of the interaction of the atoms of different materials. For this reason, Buchanan (2007) affirms that the human being is a 'social atom' and that emerging patterns (or properties) as dissimilar as segregation, social classes, collective hysteria, market collapses, fashion, ethnic wars and social revolts are products of the interaction between these 'atoms'.

It is evident that in order to explain vehicular traffic, the analyst does not need to know the shape of the cars circulating in a city, nor the specifications of their engines, nor the drivers' mood. Neither is it relevant to describe the cognitive abilities of diners in a bar, nor what their marital situation is, to be able to explain why a small dispute between two people can end in a tremendous quarrel in which almost everyone participates. Johnson (2007) thus emphasises that in theories of complexity, it is not necessary to have a deep understanding of the units of a system in order to explain their collective behaviour. It suffices to have a simplified description of the rules of individual behaviour (such as instincts or imitation skills), and a realistic specification of the structure of interaction to be able to understand the macroscopic behaviour.

In general, one can speak of Complex Adaptive Systems (CASs) in terms of both social and natural processes (physical, chemical or biological) that are characterised by the diversity, connectivity, interdependence and adaptation of their agents. Although all these systems produce positive feedback effects and, therefore, the phenomenon of disequilibrium is endemic, the functioning of CASs in the socioeconomic sphere acquires particular nuances: human beings have more sophisticated cognitive abilities and their decisions are intentional (i.e., they are usually taken for the sake of achieving an objective).

In particular, individuals, governments and organisations are aware of their capacities to change the environment in which they operate. As a result, their behaviours seek to disrupt the environment in order to achieve their objectives, or at least to improve their performance. These circumstances make the construction of a socioeconomic meta-theory indispensable. Like Gräbner (2017a), the current text suggests that institutionalist thought has the right vision for shaping the cornerstones of a meta-theory of social complexity. In particular, and unlike the 'social atom' perspective, this book considers the convenience of understanding how the cognitive-emotional attributes of human beings operate in the explanation of certain collective behaviours, beyond highlighting the topology or structure of the interaction that unfolds between people.

2.3 Simple rules and self-organisation in complex systems

Natural and social phenomena, which are ostensibly very different from each other, can be explained to some extent with reference to a universal order; that is, by considering a set of principles that go beyond the particular disciplines. The following examples demonstrate the recurrence of CASs: the flight of a flock of birds, the interaction between the molecules of a living or inanimate object, the configuration of an organism from its cells, the immune system of human beings, the organisation of an ant colony, the development of an urban agglomerate, vehicular traffic, the functioning of markets, and the movement of pedestrians on a street.

In all these cases, there is a process of self-organisation. The interaction (i.e., connectivity and interdependence) between the different agents produces a collective behaviour with characteristics that cannot be deduced from the rules of behaviour of the individual agents. The emergent properties that distinguish the aggregate behaviours arise in a decentralised way, thus making it possible to speak of a bottom-up process. Neither the synchronised flight of a group of swallows nor the organisation of ants in a colony have to do with a leader or centralised process; rather, they have to do with simple rules of local interaction that shape the behaviour of the collective.

In order to provide the reader with more clarity regarding the type of systems studied in the context of complexity, the different categories of a taxonomy composed of simple, complicated and complex systems are now described. A system is an arrangement of components that combine in order to perform a certain task. Both simple and complicated systems are designed from the top-down, with the explicit purpose of performing a specific function. In the first case, the function is carried out by grouping independent pieces. In the second case, the function is produced by assembling parts by means of a set of interconnections. In both systems, the parts or components are not interdependent, nor do they adapt to the environment. Photo albums and archival documents are examples of simple systems that are built for the purpose of classifying, while a toolbox is a simple system that is used for the purpose of storing objects in a certain order. Examples of complicated systems are watches or any other machinery designed by a person or team, and whose parts require the appropriate assembly to make their collective operation possible.

In contrast, a complex system is one whose components are connected and diverse, interdependent and adaptable. These last two attributes mean that their existence and functioning are not the product of a designer or leader but, rather, of decentralised actions. It can, therefore, be affirmed that their collective behaviour is not an intentional act. In a complicated system, the elimination of some of its components leads to system paralysis (e.g., a vehicle missing spark plugs). For its part, a complex system (such as an ecosystem) is relatively robust: it can work despite the fact that some of its components (such as particular species) disappear or fail.

Local interaction processes cause the actions of an agent (e.g., an individual, ant, vehicle, company) directly to affect those of others, without there being an added mechanism of transmission (such as price setting schemes or coordination committees). ‘Positive feedback’ predominates in the CASs, given that the consequences of the initial actions of certain agents are magnified over time by influencing the behaviour of other agents. This dynamic contrasts with that of systems that are characterised by ‘negative feedback’. In the latter, the initial effects tend to fade with the passage of time.

Negative feedback prevails in neoclassical economic models, since they incorporate equilibrium conditions that are fulfilled at all times. By assuming markets to be in equilibrium, an 'excessive' demand for a good is accompanied by a rise in its price and, consequently, a reduction in its demand. According to this conceptualisation, therefore, the possibility that purchases made by a group of individuals encourage others to do the same is ruled out. This contradicts situations that arise in a real economy on a daily basis, in which an excess of demand can be sustained for a prolonged period of time, despite the observed price rise.

Methodologically speaking, it is contended that a simple system is reducible: in order to understand its behaviour, it is enough to analyse the basic units of which it is comprised. For example, to organise a toolbox, you only need to take into account the physical characteristics of the tools in question, such as length, width, volume and weight. To explain the operation of a complicated system, you need to understand the functioning of the different parts and how they are linked together. For instance, as a first step, it is necessary to understand the functions that can be performed by a lever, a gear and a belt, in order to later explain how a lever moves a belt by means of a series of gears.

Finally, in order to understand the emerging processes of a complex system, it is not enough to identify the behaviour of its components in isolation, nor to explore the nature of its links; it is also necessary to study the interdependence between these components and their mechanisms of adaptation to the environment. For example, consumers in a market do not only take into account the change in relative prices to decide upon a purchase, but also observe what is done by consumers in their social network or by personalities who are widely recognised due to their media or socioeconomic status. In the same way, an entrepreneur chooses to offer more or less of their product not only according to price, but also seeks to generate innovations in order to exploit niche markets and, by so doing, survive the competition (i.e., adapt to the environment).

2.4 Examples of local interaction in the natural environment

The synchronised flight of a flock of birds is not explained by the presence of an alpha male that coordinates, through a hierarchy or complicated rules, the way in which the other birds must move [hyperlink 2.1]. The structure of the flock emerges from a process of local interaction in which each bird adjusts its position and direction of flight by following simple rules, which have to do with the behaviour of birds that are located in the vicinity. In other words, the synchronised flight of the flock emerges in a decentralised manner when its members emulate behaviours that are conditioned by the context in which they develop [Box 2.1].

Ants also form sophisticated, decentralised colonies with a variety of functionalities, without a queen or leader indicating the tasks they should perform. Ants specialise in specific activities such as exploration, gathering, nest construction and protection of the 'queen' ant (whose only function is reproduction), among others. As such, the colony's self-organisation is not produced by a predetermined plan. The communication between the ants flows at the local level through the secretion of pheromones. Among other aspects, this mechanism makes it possible for members of the colony to 'remember' the location of the food sources previously discovered by the scouting ants [Box 2.2].

Although an ant is neither aware of the size of its colony nor of the consequences of its actions, the size of the colony has implications for its behaviour due to the local feedback process that takes place. For example, the greater the needs for food in the colony, the more frequent the relevant information that is transmitted based on the ants' daily movements. The greater the number of roaming ants that cross over the rows that are formed to carry food, the more information will be produced by way of chemical secretion. As a result, a greater number of ants will be dedicated to this priority activity for the colony.

The collective intelligence of the ants (or 'intelligence of the swarm') allows for the creation of a complex social organisation that transcends its individual members, even though each of them has minimal cognitive abilities and a limited communication system [2.8]. A colony of ants can last up to 15 years, while the life of its members – with the exception of the 'queen' – does not exceed 12 months [Johnson 2001, Chap. 2]. The swarm intelligence is so powerful that, nowadays, it is used as a metaphor to design artificial systems with the capacity to solve highly complicated problems based on the distribution of functions between autonomous agents [see Bonabeau et al., 1999].

2.5 Vehicular traffic as an example of social interaction

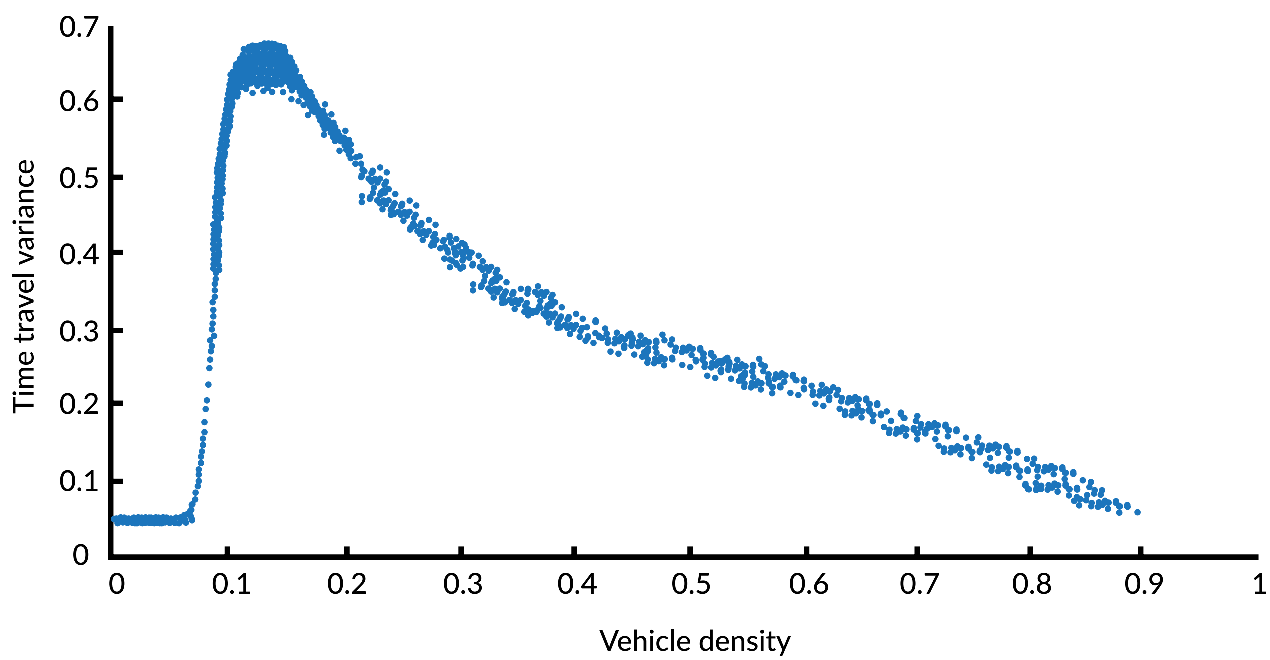
In the social sphere, agents are distinguished by their conscious response to environmental conditions. However, and despite the latter, sophisticated patterns of aggregate behaviour can be explained by simple rules of decision. A hypothetical example of a decentralised system is the vehicular traffic on a motorway, in which no authority affects the average speed of the cars by means of traffic lights, regulations or traffic officers. This example demonstrates that the so-called 'phantom traffic jam' can be formed without there being any apparent exogenous cause, be it a narrow bridge, an accident on the road, the existence of radars, or any obstacle that slows the passage of the vehicles.

The congestion is an emerging pattern that can occur simply because each driver maintains a particular distance from the car ahead, and accelerates their speed when a space opens up between the vehicles [Boxes 2.3 and 2.4]. By the measure with which the vehicular density of the road increases, the degree of interaction between the vehicles will also increase. Therefore, if the density crosses a certain threshold, a point of congestion will form characterised by waves of motorists sequentially lowering their speed. When this phase transition occurs, it is very difficult to predict the travel times of the cars, since the variance of time suddenly increases. When the threshold is surpassed, the variance gradually decreases as the vehicle density increases, until it reaches the point where the vehicles are practically detained in a formidable traffic jam [Figure 2.1].

Although bottlenecks can occur without an apparent cause, as in the previous hypothetical example, studies indicate that most real-life bottlenecks are due to the presence of some anomaly [e. g., Treiber, Hennecke and Helbing, 2000]. Namely, bottlenecks that occur as a result of lane reductions due to accidents, construction and flooding; drivers who stop to observe accidents in the opposite lanes; steep sections and poorly designed accesses and intersections on the roads; and drivers who, by performing strange manoeuvres, break the synchrony of the traffic, among other circumstances (examples of real traffic jams can be seen in *YouTube* videos, e.g., [2.11]). For an illustration of the magnitude of the bottlenecks that an anomaly can produce, see the video [2.12].

On the other hand, the 'snake' effect observed in congested multi-lane roads can also be explained by means of a system of decentralised decisions. This effect is generated when two or more lanes of a road circuit become inadvertently synchronised, in such a way that there is an alternation in the speed with which the vehicles in each lane move.

Figure 2.1 Phase transitions over travel times



* **Source:** Diagram based on Batten (2000), p. 192.

This phenomenon occurs due to the constant lane changes made by drivers who think theirs is moving very slowly while vehicles in the other lanes are moving quickly. Consequently, when a group of drivers think the same and act in parallel, their expectations are not validated: drivers who change lines have the 'bad luck' of always moving to the wrong lane.

In a city's traffic system, in which each individual does not know *ex ante* the routes that others will follow, it is impossible for drivers to choose a trajectory deductively. In the absence of information, drivers cannot determine the trajectory that will minimise their travel time. Therefore, they make their decisions based on an inductive process. In this type of reasoning, strategies are based on subjective expectations that are formed based on the detection of patterns, which are inferred from drivers' own experiences and public information. The fact that each strategy – and, therefore, each expectation – is personal, makes it inappropriate to describe this process by means of mathematical models with homogeneous agents. Thus, it is essential to use alternative tools to those traditionally employed in neoclassical economics.

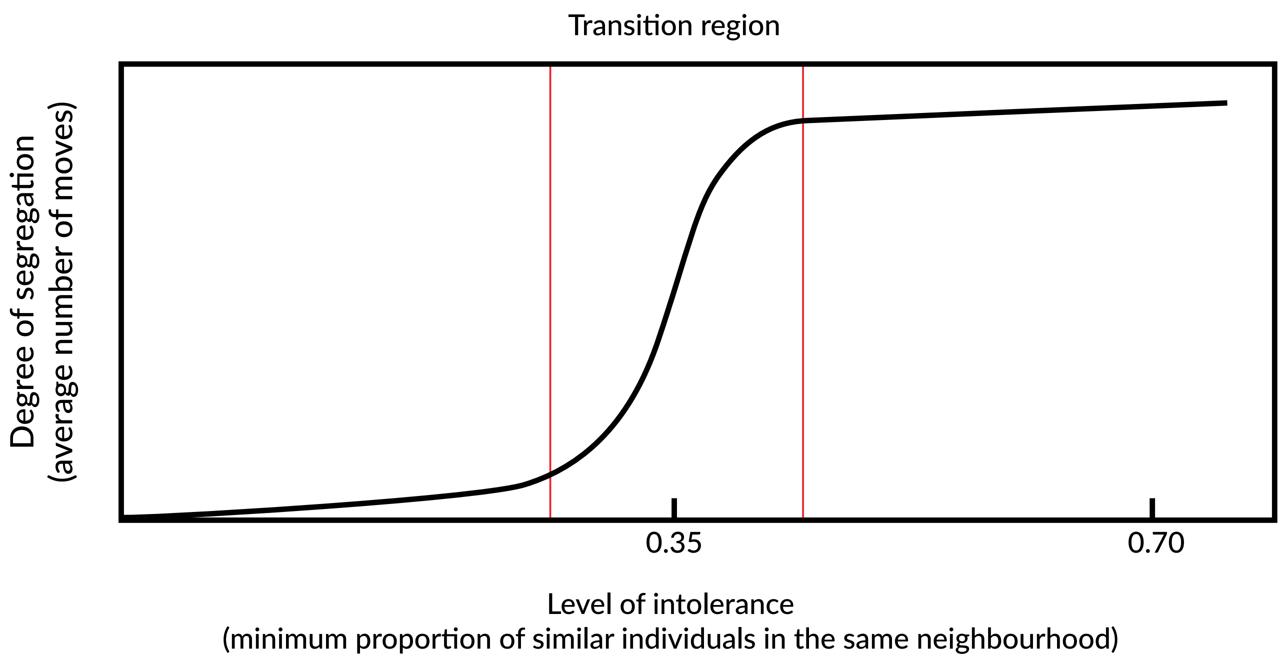
Information and communication technologies (ICT), as well as the conceptualisation of vehicular traffic as a complex adaptive system, have led to the development of diverse traffic information systems in real time in recent years. These systems have proven to be very useful to the more efficient self-organisation of transport (for more details on the subject, see Ezell, 2010 and Ettema, 2015). An example of these systems is the technology of GPS-assisted navigation developed by *Waze*: an application installed in drivers' smartphones that has been shown to be highly successful in improving mobility in streets and major roadways. Likewise, the data generated with these systems enable us to know about accidents occurring on the highways in real time which, in turn, contributes to a greater efficiency in the response times of the emergency services. In the same way, these data are being used to improve planning in the construction of infrastructure [2.16].

2.6 The effects of interdependence on social segregation

In the book *Micromotives and Macrobehavior*, the Nobel Prize winner in economics, Tomas Schelling, interprets the phenomenon of social segregation as another example of self-organisation. From the standpoint of an agent-based model (ABM), Schelling demonstrates how certain attitudes of individuals can give rise to aggregate effects that are difficult to infer directly from the simple rules of individual behaviour. In this case, people who are willing to be part of a minority and live with different individuals, end up living in segregated communities. In contrast, a scenario in which individuals are very intolerant can cause a situation of sustained disequilibrium when these people leave their neighbourhood in the face of the arrival of 'inappropriate' individuals; that is, a population that is never satisfied with their neighbourhood make-up will experience constant housing moves by its inhabitants [Box 2.5].

As in the traffic example, the collective results generated in the segregation model are the product of local interaction and the fact that agents' actions have consequences on others' behaviour. When an individual decides to move to a new neighbourhood that meets their initially desired characteristics, there is a possibility that this individual will affect the decisions of those who live there. This can produce new movements, with possible reverberations throughout the community.

Figure 2.2 Phase transition in Schelling's model



Note: In this graph, the degree of segregation is not defined in terms of an indicator of territorial concentration, but in terms of the number of housing moves that agents make, on average, before reaching equilibrium.

In the computational model, it can be observed that segregated communities suddenly appear when the threshold of agents' tolerance exceeds a certain value – the threshold that determines one's decision to stay or change neighbourhoods. This sudden change in aggregate behaviour is described as the *phase transition of the system*. In Schelling's original model, segregation emerges when the tolerance threshold increases from 33.3 to 37.5 percent [Figure 2.2]. In this diagram, the degree of segregation is measured as the average number of moves that individuals make before settling in a neighbourhood of their liking (although a definition based on concentration indices is also common). The fact that phase transitions appear recurrently in complex systems means that the interdependence between agents gives rise to non-linear processes, within which aggregate patterns are not easy to anticipate.

The original paper, published in 1971, is a seminal one pertaining to social complexity. It very eloquently illustrates that the collective behaviour of a social group does not usually coincide with the individual behaviour of the agents that comprise it. A similar process can be used to explain numerous behaviours of crowd psychology and countless socioeconomic phenomena. For example, the violence of a mob does not necessarily imply that the individuals involved present with a bellicose temperament. As Buchanan (2007) aptly comments, the great contribution of Schelling's model is its suggestion that the complexity of the social world – as well as of the natural one – can be understood based on relatively simple rules of behaviour. The latter describe important features of the psychology of the individual, without having to incorporate sophisticated elements of the human brain or the detailed minutiae of the cognitive process into the model.

The simplicity of Schelling's model – which leaves many details of reality aside – makes it very appealing, as it manages to explain that the territorial segregation that exists in towns and cities, based on religious, racial or socioeconomic criteria, is compatible with the presence of relatively tolerant societies [Ormerod, 2005, Chap. 4]. Obviously, this result does not mean that, in some societies, racism or elitism are not important causes of segregation; it simply shows that intolerance is not a necessary cause. In fact, under this model, territorial segregation only emerges within a range of levels of intolerance. Paradoxically, the phenomenon does not occur for very high values, in which case the community is located in a state of disequilibrium that causes individuals to be in continuous movement.

Schelling's model and the empirical evidence

In an econometric study, Easterly (2009) analysed the empirical validity of the interdependence between agents in order to explain segregation. This author called into question the notion that these processes cause the racial segregation that exists in different metropolitan areas of the United States. Based on a regression analysis using data from the period 1970-2000, he found that, contrary to the implications of the Schelling model, a greater number of 'white' individuals leave neighbourhoods that in previous periods had a greater presence of white people, in comparison to those that contained a higher proportion of 'mixed' individuals

However, it is worth noting the difficulty involved in testing Schelling's approach using conventional econometric methods. Likewise, the following objections to Easterly's study should be highlighted: 1) the use of a dichotomous definition of the population

– white and non-white – which is an extreme assumption, given the ethnic diversity that exists in the country under study; 2) comparing exclusively two points in time, which makes it very difficult to capture the process of agents' gradual displacement in the residential areas; 3) not taking into account important control variables such as the urbanisation policies that promoted the development of the suburbs; 4) not considering the effects of the interaction between racial and economic variables.

The non-linearity of the ABM, which originates in positive feedback processes, makes it convenient an empirical validation using the artificial data produced by means of simulations. To be more precise, the validation scheme consists of comparing whether the regularities observed in the artificial data are statistically similar to those detected in the real data pertaining to the phenomenon under study. This is the procedure used by Yin (2009), who showed that the interdependence proposed by Schelling is, indeed, a critical factor in producing a pattern of racial segregation in an area of the City of Buffalo, New York. The parameters and exogenous variables of the ABM that were calibrated include 1970, 1980 and 1990 data on racial segregation and real estate conditions, while the validation was carried out using data on segregation from the year 2000. This researcher found that the model was capable of generating the pattern of segregation observed in reality, once the interaction between movement decisions based on racial considerations and the economic restrictions making it feasible to live in certain neighbourhoods were taken into account.

Over the years, different variants of Schelling's original model have been developed [e.g., Hatnaa and Benensonb, 2012; Clark and Fossett, 2008], which is a clear example of the benefits of replicating studies for the generation of knowledge in the social sciences. The explanation of social phenomena requires collaborative work, which is nourished when new theories and tests are implemented based on the results of previous studies. As an example, Squazzoni (2012) presents a brief review of studies associated with ABM that have been seminal in the explanation of different sociological problems, among them the one identified by Schelling. It should also be noted that replications and modifications of the models can be facilitated if there exists a protocol for documenting them.

2.7 Mass movements of people in public spaces

Unlike flocks, in which birds do not know the path to follow, pedestrians walking on a street do know where they are going. However, despite the fact that human beings have consciousness, the behaviour of both groups is similar in that they display a collective harmony that cannot be predicted based on individual behaviours. In the crowded streets of a city, it can be observed that pedestrians circulate in such a way as to form rivers of people who are interspersed in opposite flows. Thanks to this emerging pattern, the number of manoeuvres that individuals have to perform to avoid collisions is reduced and mobility is made possible (see YouTube videos, e.g., [2.21]). Although it could be thought that this aggregate behaviour is a consequence of social norms that individuals internalise over time, the simulation models show that agents dispossessed of these norms are capable of producing the same type of formations [Box 2.6].

To explain this particular phenomenon – or any other collective effect that is produced with the movement of people in public spaces – sociophysicists state that in order to move, individuals combine their personal interests with their perception of the environment [Helbing et al., 2000]. The decision to move in a certain direction and at a certain speed has to rely on the signals that are received from the environment (such as the proximity of objects or people). In the event of a collision, therefore, individuals choose to modify their behaviour (e.g., distance themselves or step to one side). Based on characteristic mechanisms of fluid theories, Helbing and his colleagues suggest that a repulsion force prevents two agents from sharing the same 'personal space'. According to this metaphor, the desire to separate increases as the distance between two people decreases (for more details, consult Ball, 2004, Chapter VI and the references cited therein).

The great challenge for understanding how the masses move in public spaces (e.g., streets, parks, squares, museums, stadiums), lies in developing a good description of the rules guiding individuals' movement and taking into account that these are applied in the context of a structure of interaction. This procedure is highly suitable for designing urban and architectural spaces, the purpose being that people's movements take place efficiently and safely. These rules of behaviour vary depending on the type of space and the situation in which decisions are made. For example, when there is panic, it is important to include the factor of overexcitation that occurs when human beings are within a mass of people who congregate in small spaces (see video of human stampede at the following URL [2.26]). According to Helbing and co-authors, individuals lose their inhibitions in cases of panic and are thus willing to breach 'personal spaces'. The rejection of physical contact that normally exists loses its relevance in a context of panic: staying safe becomes the primary objective [Box 2.7].

Other important rules of behaviour have to do with people's gregarious spirit. In certain circumstances, people decide to follow one another under the presumption that some of them hold relevant information. This is a common situation in, for example, a very poorly lit nightclub that burns down. The people present will try to escape even if they do not know the exact location of the emergency doors. In the search for an exit route, the individuals' behaviour tends to be heterogeneous: some follow individualistic criteria (which may seem random to the observer), while others are guided by their gregarious instinct.

When the gregarious spirit prevails in a context of panic, the result can prove fortunate in so far as the 'herd behaviour' is not excessive. This is so since the exit becomes more expeditious due to followers taking advantage of the information provided by the 'leaders' who find an escape door. However, if the gregariousness is overwhelming, a clogging effect will emerge that will end up blocking the exits. If this happens, the human losses will be magnified. This perspective allows us to understand why catastrophic events are not eliminated when the number of doors in a stadium or auditorium is determined based on the capacity of the space, and when the decision is made to place them uniformly along the stands. In situations of panic, in which the gregarious instinct dominates, the normal rhythms of exiting and uniform flow (characteristic of a random behaviour) lose their relevance in describing people's movement.

In summary

This chapter has illustrated the appropriateness of visualising social and natural systems as decentralised processes in order to explain collective behaviour. In particular, this view is contrasted with the centralist vision of neoclassical economics, and argues in favour of the alternative approach due to its use of realistic premises. Likewise, the chapter advocates for the construction of a meta-theory that would allow for an adaptation of the vision of complexity to the study of socioeconomic phenomena, in which agents show intentionality and their interaction is conditioned by the sociocultural context. Finally, computational models are presented that simulate both natural and social phenomena. These artificial worlds facilitate the explanation of concepts and ideas that are not entirely intuitive, as well as being ideal for shifting from the vision of complexity to its formal modelling.

Questions for reflection and discussion

1 If economics is defined as the science that studies the achievement of multiple objectives through the allocation of scarce resources, how should we interpret the unemployed labour force that occurs in recessions?
2 What is the relevance of power relationships in an economic theory in which collective phenomena are explained as the product of a multiplicity of decisions taken by pulverised individuals (i.e., those with relatively few resources)?
3 Suppose that a camel is loaded little by little with bunches of straw that are placed in a basket tied to its back; what kind of emergent pattern will occur over time in relation to the weight and height of the camel, measured from the ground to the back of the animal?
4 In a given economy, there exist numerous positional goods whose perceived contribution to well-being is measured in relative terms (i.e., depending on the consumption of others). Examples of such positional goods would be vehicles, houses, parties, appliances, etc. In these circumstances, is it possible to affirm that the market allocates resources in an efficient manner?
5 Assuming that the nodes of a network represent individuals and the links represent the ties – namely, social, commercial, credit connections, etc – that exist between

these individuals, what kind of interaction structures would Walrasian economic models and non-cooperative games exhibit?

6 If preferences are stable and consistent with each other, as suggested by the neoclassical model, what is the use of advertising and marketing in a market system?

7 Consider a one-dimensional, ring-shaped space of interaction in which Schelling's rule of mobilisation takes place. In this environment, there are four dark-coloured and four light-coloured agents, which are initially positioned in an interspersed manner. It is posited that the agent is dissatisfied with his/her current location when his/her closest two neighbours are of a different colour to his/her own. In this scenario, the agent chooses to move to the closest segment (the space between two agents) in the ring that meets his/her desired requirements for settlement. If the mobilisation process is carried out in a sequential manner, show that it is possible to go from a pattern of integration to one of segregation in only three steps.

8 An architectural firm has asked a consulting company for its support in designing the spaces of a restaurant, with the purpose of obtaining the best security conditions. In particular, the architects are concerned with evacuation times in the event of a kitchen fire. The firm has the option of building the restaurant in one of the two lots that the client has available. The first of these lots has a rectangular shape of 20 x 80 m^2, while the second has a square shape of 40 x 40 m^2. Taking into account that, in both cases, the kitchen should be located on the left side of the restaurant while the exit door is located in the middle of the wall on the right side, which of the two lots will be the consultants choice, under the premise that in both cases the objective is to be able to offer the service to the same number of diners? How could the security conditions in the square lot be improved if considering that it would not be possible to open additional evacuation doors?

9 In the neoclassical approach, a market's supply and demand are independently defined by adding together the individual decisions of producers and consumers, respectively. Under these circumstances, which are the actors adjusting prices when the market operates in a setting of perfect competition?

10 Why can it be said that simulations of artificial societies help the observer to train his/her intuition?

Recommended reading

Batten, D. F. (2000). “Discovering Artificial Economics. How Agents Learn and Economies Evolve”.

Buchanan, M. (2007). “The Social Atom. Why the Rich Get Richer, Cheaters Get Caught, and your Neighbor Usually Looks Like You”.

Ormerod, P. (2005). “Why Most Things Fail. Evolution, Extinction and Economics”.

Resnick, M. (1997). “Turtles, Termites and Traffic Jams: Explorations in Massively Parallel Microworlds”.

Schelling, T. C. (1978); “Micromotives and Macrobehavior”.

Hyperlinks

2.1 https://www.youtube.com/watch?v=eakKfY5aHmY/

2.2 http://ccl.northwestern.edu/netlogo/

2.3 http://ccl.northwestern.edu/netlogo/docs/NetLogo%20User%20Manual.pdf

2.4 http://docshare02.docshare.tips/files/29778/297786800.pdf

2.5 http://franciscoquesada.com/index.php/netlogo/

2.6 http://www.red3d.com/cwr/boids/

2.7 http://ccl.northwestern.edu/netlogo/models/Flocking

2.8 http://www.youtube.com/watch?v=g7VhvoMFn34/

2.9 http://ccl.northwestern.edu/netlogo/models/Ants

2.10 http://ccl.northwestern.edu/netlogo/models/Termites

2.11 http://www.youtube.com/watch?v=goVjVVaLe10&feature=related

2.12 https://www.youtube.com/watch?v=HRluOTrZOWE

2.13 https://www.youtube.com/watch?v=Uz5uxAsrbwI

2.14 http://ccl.northwestern.edu/netlogo/models/TrafficBasic

2.15 http://ccl.northwestern.edu/netlogo/models/TrafficGrid

2.16 https://www.waze.com/es-419/ccp

2.17 http://www.econ.iastate.edu/tesfatsi/demos/schelling/schellhp.htm

2.18 https://www.youtube.com/watch?v=AZlWOykGzYg

2.19 http://kjfinn.wixsite.com/segregation

2.20 http://ccl.northwestern.edu/netlogo/models/Segregation

2.21 http://www.youtube.com/watch?v=_nYFGerwpDA&feature=related

2.22 http://www.trafficforum.org/somsstuff/pedapplets/Crossing.html

2.23 https://www.youtube.com/watch?v=yW33pPius8E&index=1&list=PLk7tDwnvsZsSayCfB-65A6qRLSm5FpKvrY

2.24 http://www.coss.ethz.ch/publications/crowds.html

2.25 http://ccl.northwestern.edu/netlogo/models/Paths

2.26 http://www.youtube.com/watch?v=eu4DlwE0Bu8&feature=related

2.27 http://angel.elte.hu/panic

Box 2.1 The synchronised flight of a flock of birds

To observe a flight simulation of a flock of birds (or the harmonic swimming of a school of fish), it is suggested that the reader use the *NetLogo* platform available on the Internet at URL [2.2], which can be downloaded at no cost. Prior to using the platform, the following tutorials are recommended reading *(User Manuals → Web): Sample Model: Party and Tutorial # 1: Models*. Once the software has been installed, the *File* tab should be opened and the following sequence carried out: *Files → Model Library → Sample Models → Biology → Flocking*.* On the Internet, the *NetLogo* user's manual [2.3] is also available, along with tutorial notes put together by Steven O. Kimbrough [2.4], and a book for learning to program written in Spanish by Francisco Quesada [2.5].

The information tab of the platform's interface outlines the three simple rules that guide the flight of each bird: (1) 'alignment', telling them to continue their flight in the average direction of those in the vicinity; (2) 'separation', signalling to them not to get too close to their neighbours to avoid collisions and (3) 'cohesion', which tells them not to move too far away from the flock to avoid predator attacks. These rules only affect the location and direction of the birds, since they all move at the same speed. At the moment of starting to run the model, the birds are 'seeded' in the environment in random positions and directions, as described in the interface screen (Diagram a).

The application of these three rules is limited to the neighbourhood (or territory of a certain radius) of each member of the flock, so that the harmonic flight of the birds is the emerging order resulting from the local interaction (Diagram b). With the help of the interface sliders, which assign a value to the model's parameters, the reader can answer the following questions: what happens if the vision (or range of action) of each bird is relatively small? With what level of vision does the flock move in a single compact group? What is the visual effect of the minimum separation between the birds?

* Wilensky, U. (1998). *NetLogo Flocking model*. [2.7]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

This model was created in 1986 by Craig W. Reynolds, 1998 Oscar winner for his contribution to film animation through the use of computers. Among other films, the flock animation was used in Tim Burton's film *Batman Returns*, made in 1992, with the purpose of simulating a swarm of bats and a flock of penguins [2.6].

Diagram (a): initial conditions

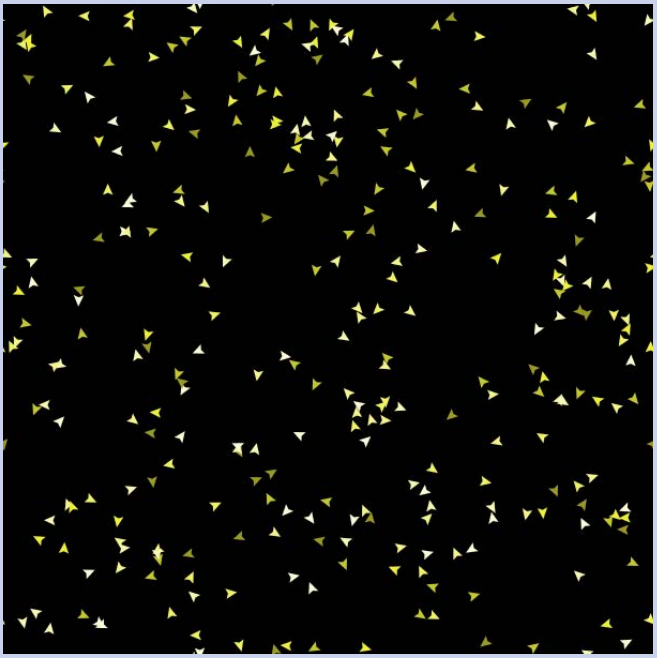
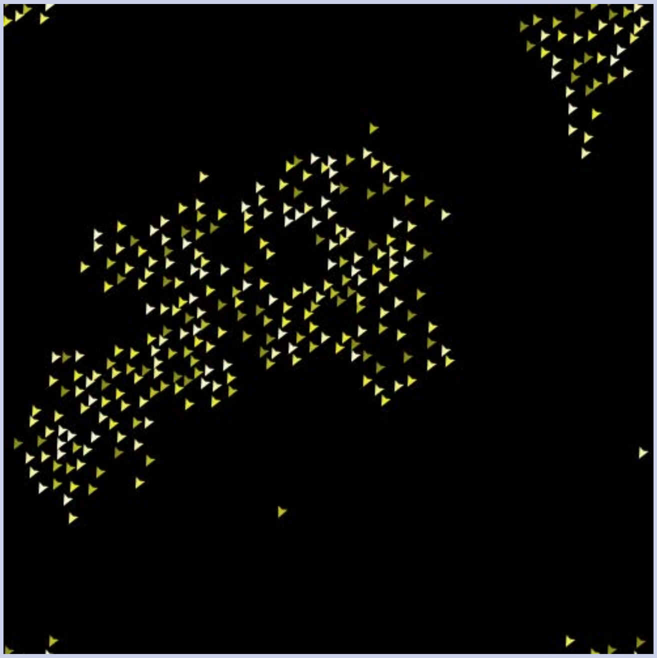


Diagram (b): synchronised flight



Box 2.2 The self-organisation of an ant colony

In the *NetLogo* model library, there is a programme that analyses, *grosso modo*, the mechanism of food collection in an ant colony. The details of this model are presented in Resnick (1997). This program can be accessed using the following sequence: *File → Model Library → Sample Models → Biology → Ants*.* As with other CASs, the simple rules that guide the behaviour of each ant produce a sophisticated organisation within the colony. Each ant (the software agent depicted in red) makes a series of random movements and, when it finds food (Diagram a), it takes this towards the nest (purple area). On the way, it secretes a chemical that the other ants smell in order to guide them towards the food source (blue areas of different tones). By following the chemical trail and collecting more food, the ants secrete more pheromones (the green tone of the path that becomes lighter). These then send the signal that food is plentiful and that more working ants are required (Diagram b).

Given that the chemical evaporates over time, the ants tend more quickly to exploit the food sources closest to their nest. Consequently, without following a previously outlined plan, the ants exploit the sources in a sequential manner, from the closest to the most distant. The ants that explore the territory in a random way find the nearest sources more easily, which allows them to reach a critical mass large enough to sustain the smell of the chemical and to guide more ants. The reader will better understand the influence that decentralisation has on the food collection if s/he engages with the following questions: what happens when the number of ants in the colony is relatively small? When two sources of food are equidistant, which one will be exploited first?

Another well-known biological model illustrating self-organisation is one that studies the construction of a pile of wood chips by a termite colony. The *NetLogo* sequence for accessing this model is as follows: *File → Model Library → Sample Models → Evolution → Termites*.**

* Wilensky, U. (1997). *NetLogo Ants model*. [2.9]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

** Wilensky, U. (1998). *NetLogo Termites model*. [2.10]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Diagram (a): random search

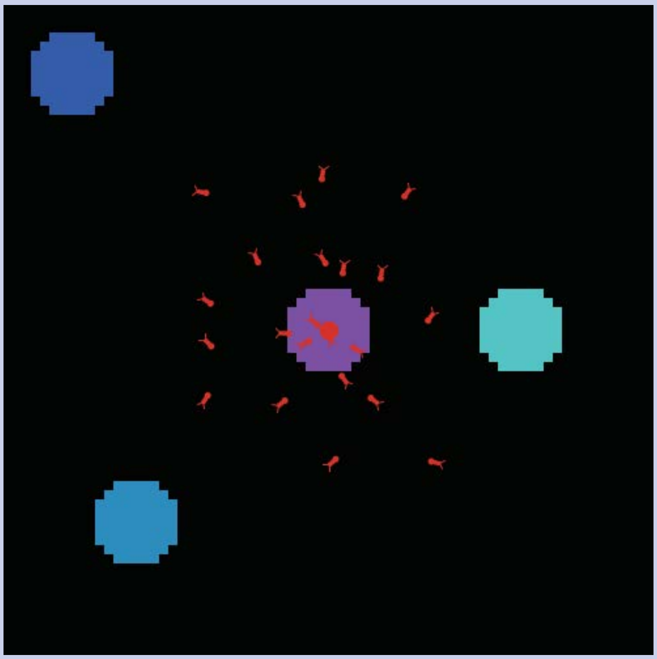
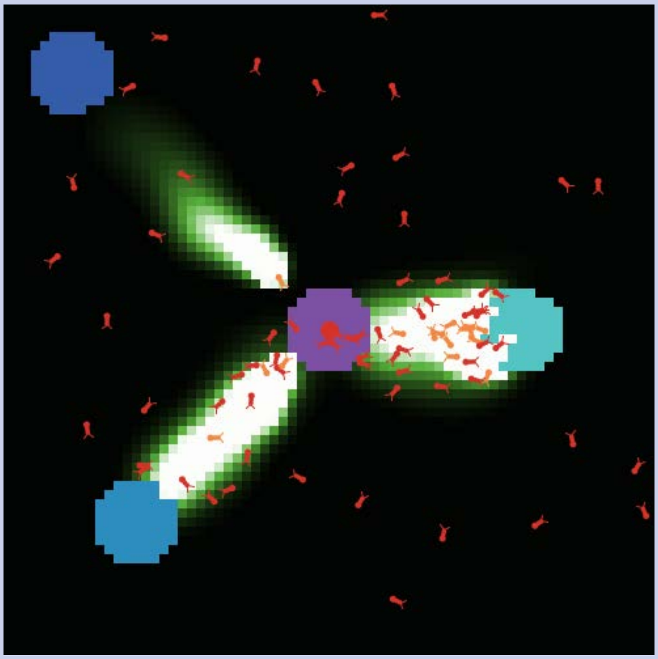


Diagram (b): pheromone secretion



Box 2.3 Vehicular traffic on a motorway

A very simple model of vehicular traffic is available in the *NetLogo* programmes file under the sequence: *Model Library* → *Sample Models* → *Social Sciences* → *Traffic Basic*.* Once the analyst has determined the number of cars and the accelerating and braking speeds, the results that are presented in the simulation interface show the maximum and minimum travel speeds of the vehicle fleet, as well as the way in which the speed at which a 'flagged' car moves forward is modified. The latter is chosen at random in the algorithm and is identified on the screen with the colour red and a halo (see Diagrams a and b).

The simulation starts by randomly defining the position of the vehicles on the road. In the course of the vehicle trajectories, a surge can be observed. In this, the cars move forward while the hubs of congestion move backwards (from right to left). Under this decentralised perspective, what do you think happens when the number of vehicles is modified to 10 or 35? What would happen if the vehicles were equally spaced out on the road, instead of being randomly positioned? For further details on *Traffic Basic*, see Resnick (1997).

An experimental analysis of 'phantom jams' (i.e., those occurring without the presence of bottlenecks) is presented in Sugiyama et al. (2008), where the reader is recommended to watch the supplementary video material. For a more in-depth discussion of vehicular traffic conceived of as a complex system, see Chapter 6 of Batten's book (2000) and Chapter 7 of Ball's book (2004), and the references cited therein. The decentralised nature of traffic is felt in a forceful manner in the daily life of the motorcyclists, cars, cyclists and pedestrians who pass through cross-roads in Hanoi. A video of this phenomenon can be seen at [2.13].

* Wilensky, U. (1997). *NetLogo Traffic Basic model*. [2.14]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Diagram (a): motorway

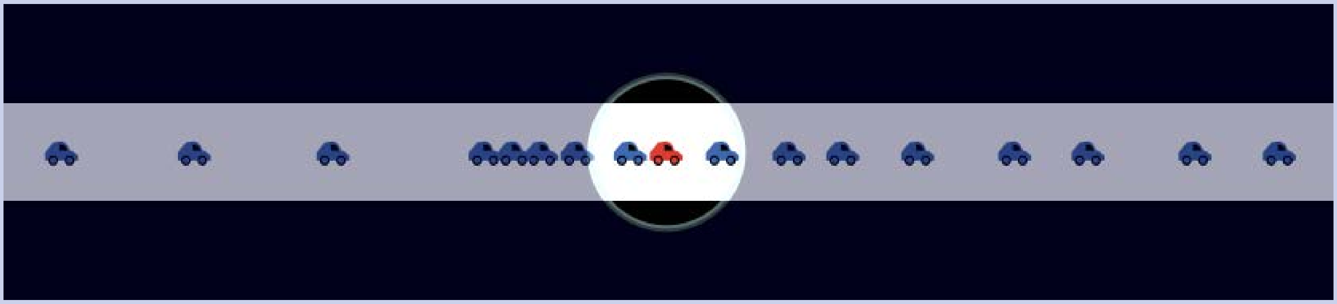
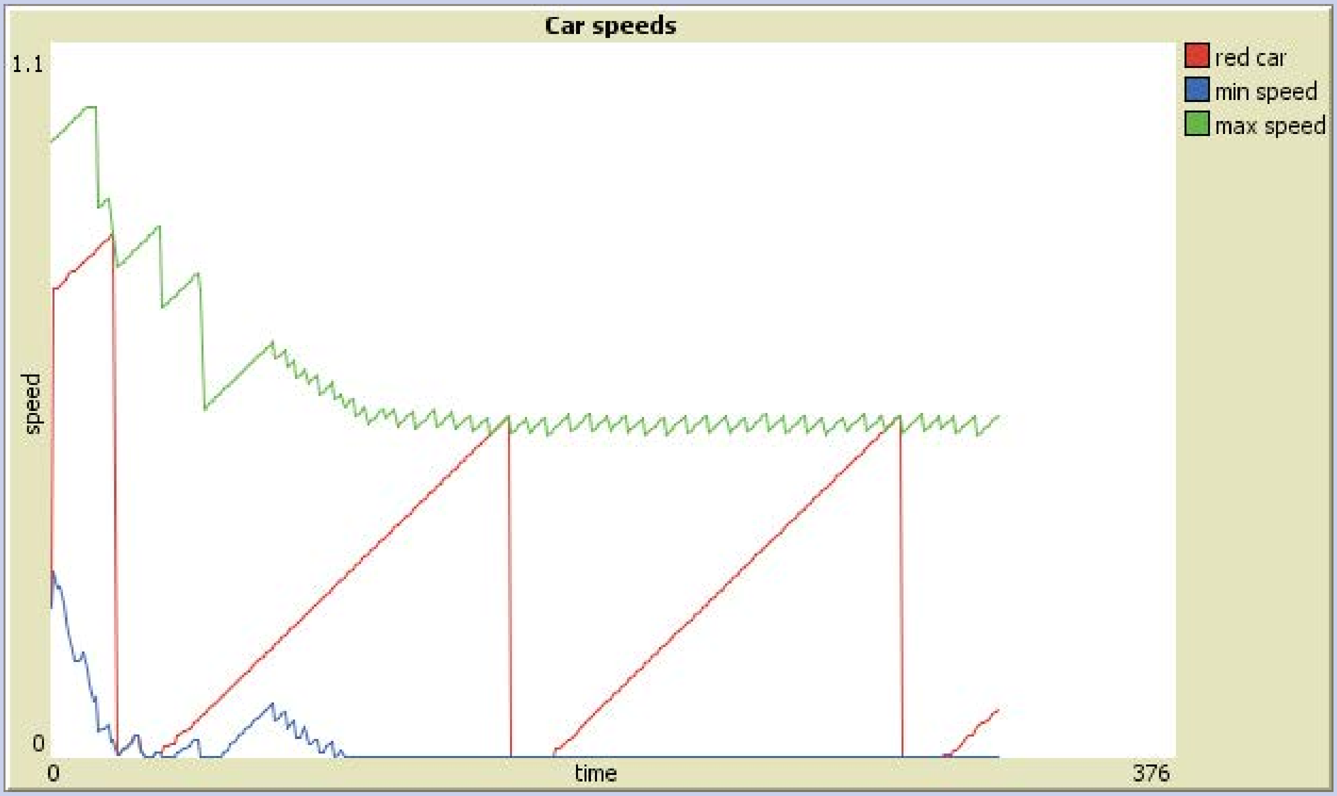


Diagram (b): speed



Box 2.4 Vehicular traffic in a city

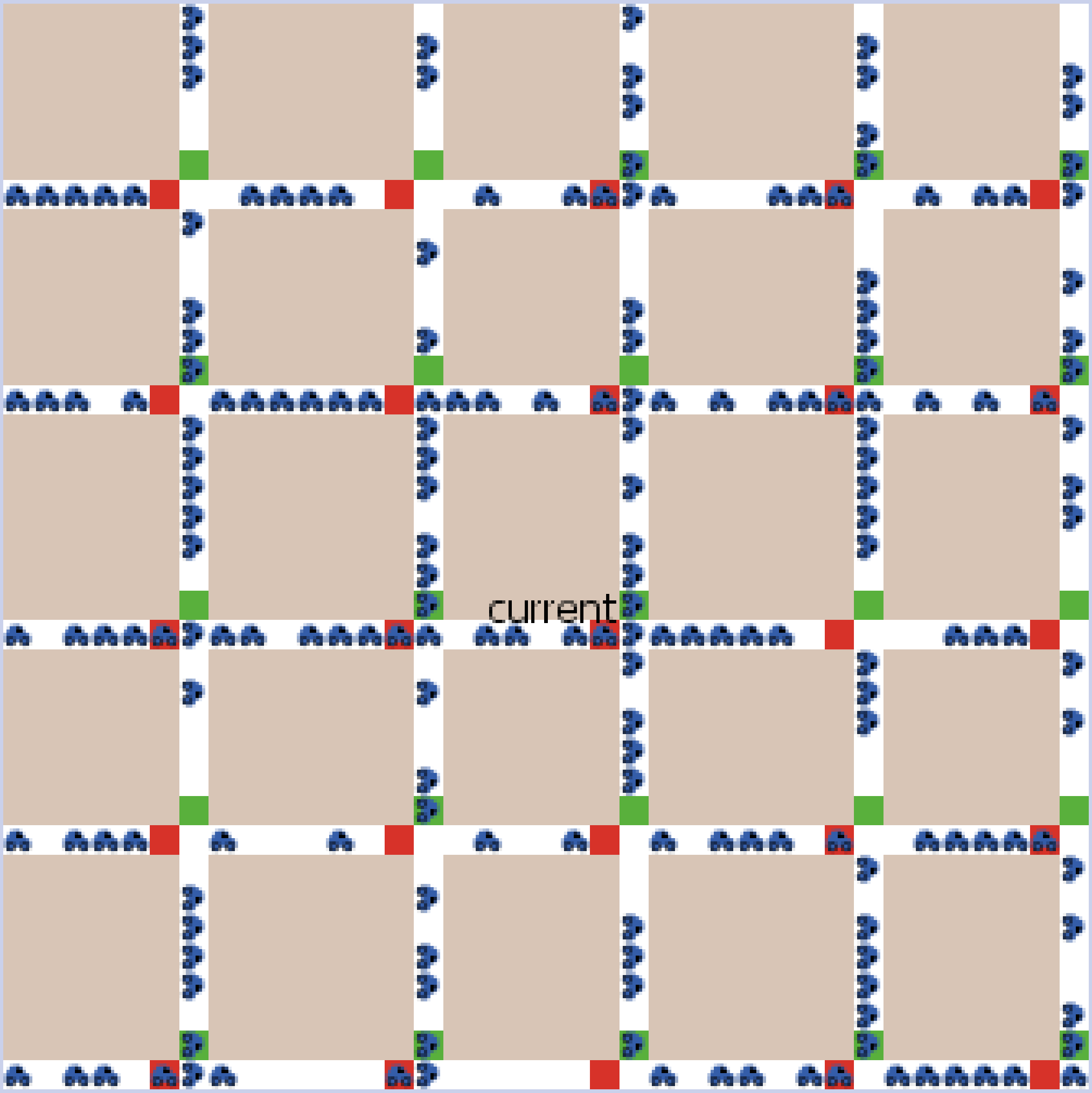
Another model of vehicular traffic in *NetLogo* exemplifies how agent-based simulations, in addition to being useful for understanding why congestion occurs, help to study the impact that public policies can have in the real world. Traffic Grid* simulates a segment of the streets of a city (see Diagram), in which each vehicle maintains a different speed depending on the distance it keeps from the vehicle in front (i.e., a greater distance means greater acceleration). In this virtual neighbourhood, cars follow certain traffic rules such as stopping at a red light and not exceeding the speed limit.

In this programme, the analyst can detect the repercussions that the change in a particular road rule has on traffic flow, such as modifying the time period for the automatic change of lights, or manually adjusting the traffic lights at a troublesome junction. When observing the results of the different traffic runs, the following questions can be answered: what would happen if the light changing cycle becomes very long or very short? Is it possible that an increase in the speed limit would reduce the average speed of vehicle flow? Is it possible to specify a vehicle load level such that cars could keep circulating despite a blackout in the city?

* Wilensky, U. (2003). *NetLogo Traffic Grid model*. [2.15]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Two other programmes related to vehicular traffic are presented in the (unverified) *Social Science* folder of the *NetLogo* model library: *Traffic 2 Lanes*, *Traffic Intersection*.

Diagram: the streets of a city



Box 2.5 The segregation of communities

A computational model of social segregation is available in the *NetLogo* programmes file, which can be accessed via the following sequence: *Model Library* → *Sample Models* → *Social Sciences* → *Segregation*.* In the interface of this model, the observer specifies the tolerance threshold of the individuals (green and red), for which it selects the minimum percentage of people of the same colour who should be living in the neighbourhood, in order for the individuals to be content to live there and to not want to move. Upon starting the simulation run, the people are placed at random in the 'lots' of the different neighbourhoods (see Diagram a), echoing the notion of integrated communities. When the percentage of different individuals in the neighbourhood exceeds the level marking the threshold of tolerance, the person randomly moves to an empty property (the black sites of the grid) in another neighbourhood that fits his/her preferences. Given that individuals are sequentially activated and act under the same type of behaviour, a neighbourhood that initially seemed appropriate may end up not being so. Consequently, those people who are not satisfied any longer have to move in the next period. The simulation stops only when all the individuals are content with the composition of their district (neighbourhood or set of sites around the individual).

When individuals are relatively tolerant and have, for example, a preference for neighbourhoods where at least 30 percent of people are like them, the simulation produces an artificial community that shows a high level of segregation. This pattern can be identified by clusters of the same colour, as seen in Diagram (b). This scenario occurs despite the relative individual tolerance and the fact that the neighbourhoods initially contain, on average, 50 percent of individuals of the same colour. In other words, micro motivations cannot be inferred by solely considering macro behaviour.

In contrast, a scenario of continuous disequilibrium, in which there are constantly agents in motion, emerges when a high level of intolerance is established.

* Wilensky, U. (1997). *NetLogo Segregation model*. [2.20]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

There are diverse questions that can be addressed with this model of interdependence: what effect is exerted when there are few empty spaces to move to in cases of dissatisfaction? At what tolerance threshold can we observe average levels of segregation that are higher than 90 percent? At what tolerance threshold does a second phase transition occur, in which segregation disappears and the model comes to be in constant disequilibrium?

Other demos of the Schelling model are available on the Internet. One of them, written in C# by Chris Cook, can be downloaded at no cost from the following URL [2.17]. This demo, in addition to being very well documented so as to enable the reader to run the simulation, presents some interesting variants: the possibility that an individual dissatisfied with the neighbourhoods of a particular community will migrate to another community, including individuals of three colours, or that only a percentage of individuals will make their decision in each period. As the reader can observe when performing the runs with three colours, the phenomenon of segregation is no longer so evident to the naked eye, which gives rise to the following question: in what other way can an index of segregation be constructed?

For a detailed explanation of Schelling's segregation model in *NetLogo*, it is suggested that the reader consult Martin Hilbert's YouTube video [2.18]. In addition, Kyle J. Finnegan's web page [2.19] presents other articles with revisions of the model, as well as some real applications of the phenomenon of segregation: political ideologies, business location selection, residential segmentation, and land use planning.

Diagram (a): initial conditions

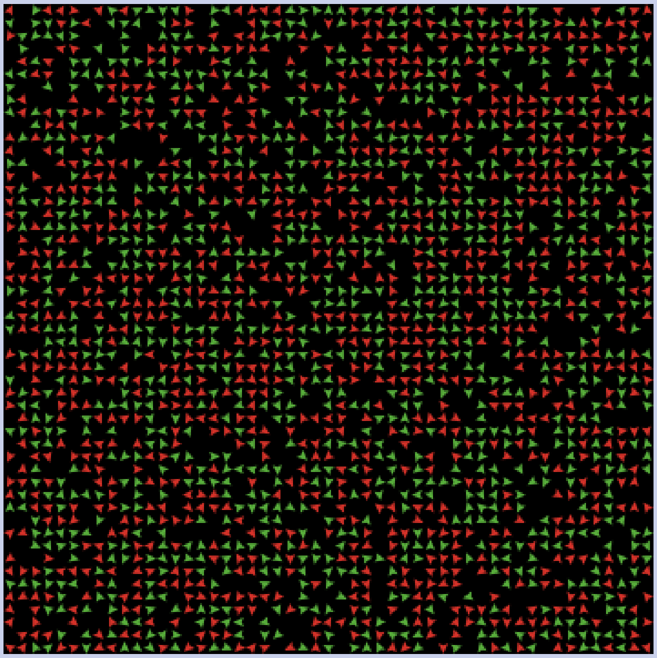
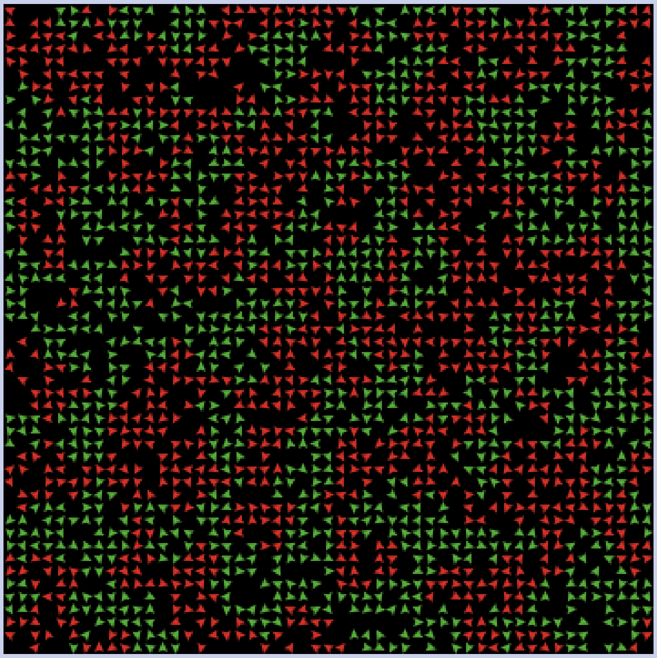


Diagram (b): segregation equilibirum



Box 2.6 Circulation of people in public spaces

Diagram (a) shows the result of a simulation in which pedestrians move in opposite directions on the same sidewalk.* The individual behaviour of the agents (arrows) produces a macroscopic behaviour in which several flows are formed with opposite currents (red or blue arrows), through which the pedestrians pass. This form of self-organisation explains why trees, or any other type of obstacle that stands in the way, contributes to reinforcing the presence of opposing currents. The obstacle causes individuals to be forced to take a step to the right or to the left, which encourages the people closely behind them to adopt the same decision and thus reduce the possibility of colliding with those who come towards them.

This same logic serves to explain why people who pass through a door in opposite directions do so in blocks. For a certain density of individuals located in adjoining rooms, it can be observed that when one of them decides to interrupt the opposite flow, others follow, thus forming interspersed lines of people who pass through the door, as shown in the Diagrams (b, c). Applying a linear logic, one would think that the greater the bottleneck occurring in the doorway, the greater the need to expand its width. However, this is not the most efficient solution for improving mobility: constructing an obstacle contributes to people forming lines more quickly. For this reason, instead of having a wider doorway, it would more beneficial to open two doors separated by a column. When these doors do not have 'entry' and 'exit' signs on them, as in museum rooms, a preference for each door arises spontaneously – an attitude that reduces the need for blocks of visitors to intersperse in order to pass.

* These simulations are available at [2.22]. Another video with an interesting simulation of the formation of interspersed pedestrian flows can be found at the URL [2.23]. To explore this problematic in greater depth, consult the publications of Helbing and his colleagues on the web page [2.24].

** A simulation model analysing the decentralised generation of sidewalks in a public park is presented in Grider, R. and Wilensky, U. (2015). *NetLogo Paths model*. [2.25]. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Diagram (a): opposite flow currents

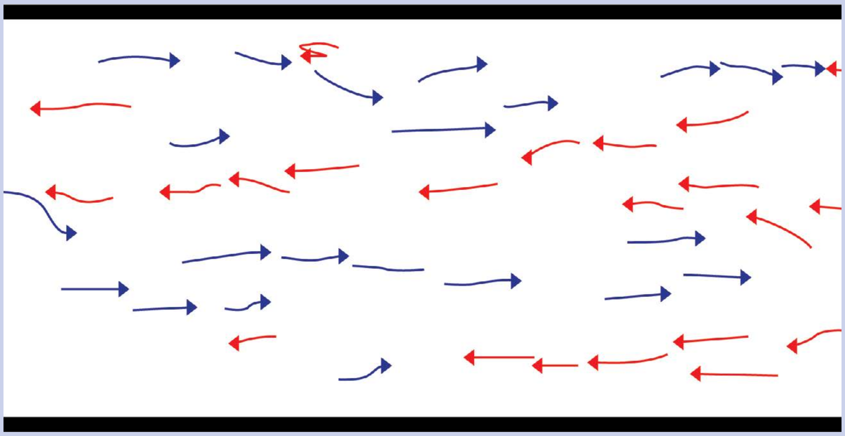


Diagram (b): the red agents' turn

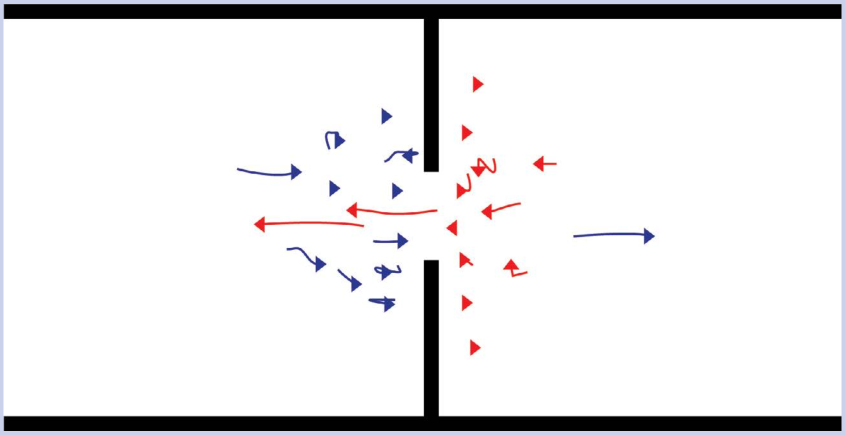
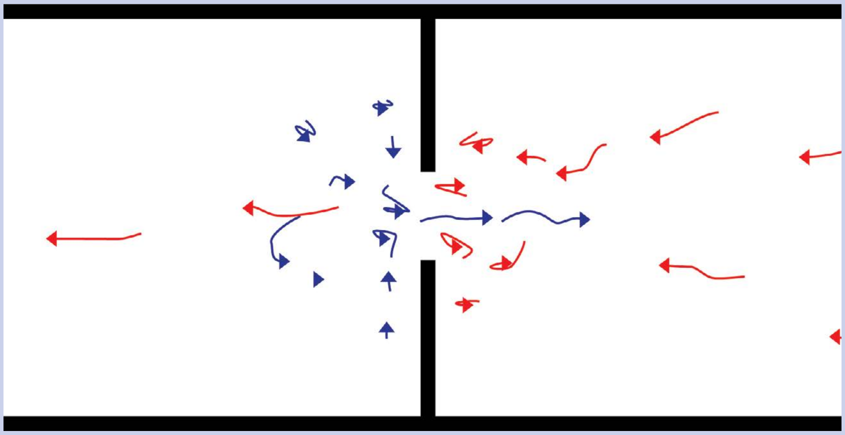


Diagram (c): the blue agents' turn



Box 2.7 Evacuations in situations of panic

When people are calm, they maintain a prudent distance that allows them to maintain a steady speed of movement and evacuate a space without setbacks. However, when modelling people's behaviour in situations of panic, it is advisable to eliminate the restriction that prevents them from touching so as to incorporate an element of friction that makes it difficult for them to move once contact is made (see Diagram a, where people are illustrated with the orange dots).* The model should, therefore, include the possibility that the pressure exerted by several people will injure those who are stuck, which will, in turn, produce human obstacles that make movement even more difficult.

Using a simulation model, Helbing and his co-authors show that if one begins with very low travel speeds, the time taken for people to evacuate a space decreases as the speed increases (see Diagram b). However, once past a threshold marking a panic situation, the desired higher speed causes the evacuation time to increase. If mass hysteria occurs, the stampede will engender such an impediment that people will begin to suffer injuries (see Diagram c, where fatalities are illustrated with grey dots). To avoid this unfortunate outcome, an alternative would be to build robust columns in front of the exits, the objective being to avoid excessive pressures that produce fatal results (see Diagram d). Again, such an architectural design challenges our linear perspective.

* **Source:** Simulations available at [2.27], for further details see the article by Helbing et al. (2000).

Diagram (a): clogging due to friction

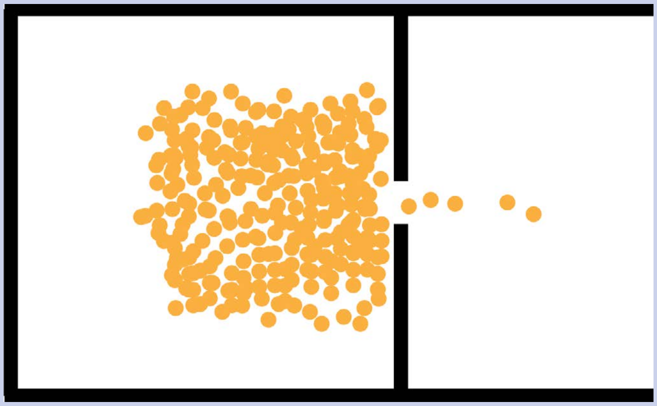


Diagram (b): from calm to panic

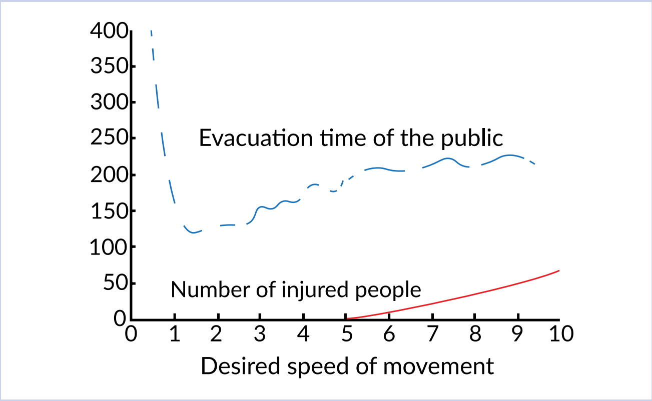


Diagram (c): stampedes and fatalities

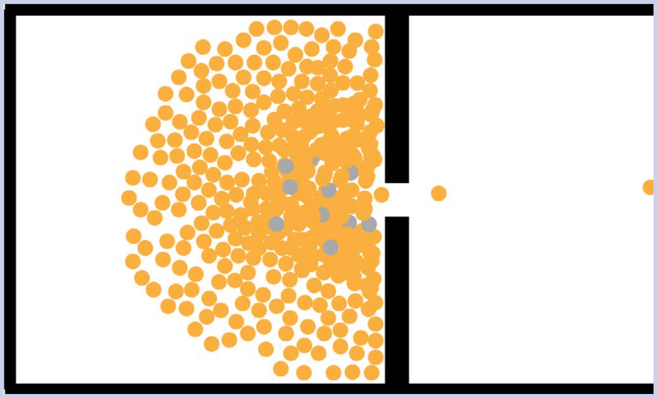


Diagram (d): prevention column