CHAPTER 1. INTRODUCTION

An interesting question is:

What happens whenever a particular theory no longer provides a full description of a given system but only a set of restrictions to which it must abide? Consider:

a) An isolated container of two separate, non-interacting ideal gases. Whenever the partition between them has been removed and they are allowed to mix, as a result of diffusion the number of non-equilibrium configurations will be larger near those corresponding to better mixed states; these relative numbers provide a probability for the macrostate to evolve and indicate its direction. In this case the law of increase of entropy both restricts and describes evolution of the macrostate, based on the likelihood of the microstate configurations from previous configurations.

b) A many-electron atom. A set of descriptive statements, such as effective charges, the Pauli exclusion principle, Coulomb interaction, and spin-orbit coupling together can be represented by a compiled set of restrictions, the Hund's rules. These intend to determine the lowest ground state configuration and the order of atomic energy levels in terms of quantum numbers; however, these constraints cannot foresee some exceptions found in the assumed regimes to which Hund's rules are applicable.

The difference between both examples is how complete is each representation in giving a full phenomenological description. The apparent failure of the Hund rules comes directly from effects not foreseen by the interactions concerned at their formulation, and reflects a lack of refinement in the theory. As we compare frameworks that give ‘sufficiently accurate’ descriptions due to refinement in their background theory, against those consisting of an arbitrarily large set of restrictions only, we see that in the latter it is often the case of emergence of degrees of freedom not explainable in terms of the background theory or constraints. Could some of them be associated to the feature of strategies, competence, even evolution in the biological sense?

K. Sims made in his work on virtual creatures[1] a connection between directed graphs and the morphology and control capacities of a population of virtual three-dimensional ‘creatures’ generated by an evolutionary algorithm. By having a fitness measure associated with different strategies with respect to a goal (such as swimming, hopping, control of a resource, etc.), and simulating evolution via optimization techniques, it was observed that some successful strategies emerged as preferred.

Figure 1. Locomotion is subject to fluid mechanics, but which type of it is the most efficient?[a]

Even when none of them can violate any of the restrictions imposed by their physical world, some configurations or strategies do have a better payoff than others. Could a distribution of privileges in the space of individuals be inferred from the physical framework in which they hop, swim, etc? If so, what roles do the building blocks, the simpler, preceding physical substrate of the individuals, have? Unlike sciences involving the study of adaptive systems such as biology, the physical sciences lack and are indifferent to 'goals'. J. Holland puts this as: standard theories in physics "concentrate on end-points", in contrast to those systems showing adaptation, which "never get there"[2].

Just as the term 'building block' refers to a resource to construct an object at a higher level, it also suggests the question of how the particular organisation that follows, the hierarchy inherent to the building process, is. We address the question of a bottom-up approach of study and what have been the results of its application to some problems in physics, thus aiming to relate it to features of complexity in general.

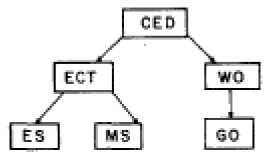
1.1 Building blocks in the different sciences

1.1.1 The physical sciences

The organization in hierarchies of the structure of the universe has become well known perhaps due to the reductionist approach that has been characteristic of much of the development of physics. The intuition of a structure of blocks which are the building blocks of a following stage of association is pervasive to many physical systems. For example, on a quick inspection of the dimensional ranges of matter: we have quarks being the subatomic particles, constituents of the higher order composite particles nucleons. Via electromagnetic forces atoms are constructed, which cluster in molecules according to the laws of chemistry. Molecules are the building blocks that give origin to either composites of biological interest and their further levels of organisation; or of non-biological interest, which are the substrate for the structures studied in a range of sciences that goes from chemistry to planetary geology, or stellar dynamics. Stars and stellar systems shape galaxies, the components of the clusters and superclusters of galaxies that form the known universe.

The physical sciences attempt to give explanations as to how these blocks organise according to the rules that describe their interactions with some other blocks, and define at what scale these events occur. Remarkably often, what happens at one level does not intervene significantly at the next. Nuclear matter can be studied in a largely independent way to the phenomena studied by quantum chromodynamics. As atoms seem to aggregate in line with properties dependent to their orbitals alone, what happens inside the stable nucleus contributes little to the particular chemistry of the system. Statistical mechanics and condensed matter physics rely more on the collective behaviour rather than on the specific orbital arrangements of their building blocks, in order to describe uniform physical properties. In these cases the macroscopic theory is mostly independent of the degrees of freedom which are involved in the underlying theory, and are effective in representing a collective behaviour of their constituents, which have a characteristic scale defined by an energy range. Phenomena happening at different characteristic scales will seem independent as long as the energy scales involved are clear-cut and do not overlap.

Fairly related to scaling limits, another type of hierarchy in physics is the logical conceptual structure of the science itself. Physics is one key exponent of scientific reductionism, and this is reflected in the usual manner in which systems of knowledge are developed. Under certain assumptions, concepts on particular phenomena are generated which are later absorbed by more general ideas valid over a wider range; these serve to formulate a major theory. For instance, the conceptual structure of classical electrodynamics:



		ω	λ/a
ECT	QUASISTATIONARY CURRENTS, CIRCUIT THEORY	FINITE	$\gg 1$
MS	STATIONARY CURRENTS, MAGNETOSTATICS	0	∞
WO	WAVE OPTICS	FINITE	1
GO	GEOMETRICAL OPTICS	∞	0
ES	ELECTROSTATICS $c = \infty$	0	∞

Figure 2. Finer logical structure of classical electrodynamics, classified in terms of λ/a and ω. λ and ω are the wavelength and frequency of the electromagnetic disturbance, and a is a length specifying the size of the measuring apparatus[b].

A domain can be conveniently reduced to study particular phenomena when a set of a priori assumptions is set, without need to refer to the 'parent' theory. L. Tisza puts the parent fundamental theory in contrast with the sub-domains which are phenomenological, reduce to the fundamental system, and are "directly related to *physical reality*"[3]. Typically, models from the sub-domains are better suited to experimentation and serve as reference to higher level frameworks. It is the "depth" of content which matters in elaborating a hierarchy of the conceptual structure of the science. How are these building blocks arranged is of interest for the history and methodology of physics.

It should also be pointed that such building blocks are not present only in the structure of some systems but also in the dynamical aspects of their evolution. For instance, in the study of quantum gravity, a requirement of background independence leads to assume that the configurations of space-time need to emerge from the underlying equations of any proposed model. In particular, how our familiar continuum space-time arises from the dynamics of some fundamentally discrete building block is a question of current research[4].

1.1.2 The biological sciences

A typical example where a hierarchy is notably evident is in the construction of the different levels of organization of interest to the biological sciences. Next we review the formation of higher order, differentiable entities emerging from the aggregation of lower level entities: be they an organism, a taxonomic rank, or the relationship between living matter and other, living or non-living.

In general, biomolecules exist as aggregates of organic molecules which give them shape and size as they link monomers and polymers; and/or facilitate chemical reactions as they constitute functional groups. Biomolecules in turn are the building blocks of complexes which give diverse possibilities to create both constitutive modules (cytosol, membrane, etc.) and operative modules (protein complexes, enzymes) which will form the next levels of organization, organelles. These are the subunits of the cell. Cells in turn are the smallest living units (and the end level of anatomical organization for prokaryotes). For eukaryotes the next levels follow: cells aggregate and interact accordingly as they form tissues; a diversity of these is often required to form the next effective units, organs. Altogether they are able to form higher level systems (circulatory, nervous/sensory, skeleton, etc.) each necessary to comply with specialised needs. Thus the integration of these interdependent yet differentiated systems yields the canvas for an individual organism, which is required to be able to maintain homeostatic equilibrium.

For biological systematics, the organisms with a similar genetic package are members of a same species, the lowest level taxon. Criteria of similarity in the genome of species serve to compile a number of these into higher level taxa according to genotype classifications. It follows all the way up to the most fundamental genetic and evolutionary differences, leading to classification by domains.

In addition, the organism constitutes the seed of the ecological hierarchy organization: an aggregate of members of a species in given space and time is branded a population; a collection of interacting populations of different species conform a community. Along with the environment, we attain more or less defined portions of highly interdependent living and non-living matter, ecosystems. These constitute the Earth's biosphere. We can also consider the basis for the dynamical properties of systems biology, to find that the building blocks responsible for featuring much of the concerned phenomena in the biosciences are associated to the genetic substrate of living matter.

1.1.3 Engineering and the sciences of the artificial

It has been the case that many questions about physical systems are reduced into information existing at the smaller scales and the ultimate basis, if any, of this reductionism is still unknown. In biology, systems are 'ultimately' represented by genetic information. In the case of the common ground of engineering and the sciences of the artificial, design (understood as formulating plans which seek at changing existing situations into preferred ones[5]), their substrate is learning on the environment and its structure, which often leads to guidelines for performance.

Genetic algorithms, a branch of evolutionary computation, are a common search technique to solve optimization problems. Binary string representations of the genotype of an individual are subject to evolution via variation operators inspired in the evolutionary biology and population genetics: inheritance, selection, mutation and recombination; these are possible solutions to an optimization problem. A genetic algorithm follows in general the set of steps:

1. Gives initial conditions “population initialization”
2. Selects those solutions which are best in terms of a given fitness criterion, via some selection method.
3. Makes use of the defined variation operators.
4. Repeats steps 2 and 3.
5. Terminates.

A genetic algorithm requires the definition of a fitness criterion relative to the representations used in the population of candidate solutions. The method of selection can be problem-dependent, for instance it can be a function of all candidates, or of specific regions in the space of solutions. Also, the variation operators may have more than one input (for instance, mutation requires only one ‘parent’ string, versus crossover which requires more than one). Crossover itself is of importance for the implementation of the Holland’s schemata that will be discussed in chapter two, which are the foundation for a formalism based on genetic algorithms aimed to solve questions of complex systems in their informational basis.

1.2 Complexity

A goal of this work is to study building blocks in a general context of complex systems, a category pervasive to phenomena across different disciplines and not yet well understood. One statement about complexity was given by H. Simon[6] in terms of the properties and interactions of the components of a system: when these are defined, “it is not a trivial matter to infer the properties of the whole”. Two ways to define complexity have been proposed[7]:

> *As a process of understanding a system.* The difficulty entailed to this is often reflected in the attempt to determine measures of complexity, such as measurements in space (e.g. the algorithmic information content[8]), or in time (e.g. the logical depth of an object[8,9]) of a given trait of the system. However, representing information of a system often depends on the terms under which it is described; hence giving objective, general definitions of the measures may not be simple.
>
> *As a property of a system.* A system is said to be more complex than other if it can be represented effectively by different models at different scales[10].

A complex system involves many components (“agents”), which underlines the nature of the interactions they concern. If these highly coupled, the nonlinearity of the system will generally pose a higher sensitivity to initial conditions. As a result, many pathways are available and the process is open-ended.

One interesting feature associated with complex systems is emergence. This occurs when from local (microscopic) interactions, usually nonlinear, global (macroscopic) structures appear without seeming logically consequent of the local laws. For example, the rules which govern computation are more or less independent of their physical substrate, be they transistors, vacuum tubes or neurons[11].

In the other case, less coupled interactions between the system's components allow a simpler analysis with the techniques of probability theory and statistical mechanics. This is a feature of 'disorganized complexity'[12], in contrast to the previous example of emergence, the hallmark of so called 'organised complexity'. It has been claimed[8] that complexity lies in a region between total order and complete disorder; such systems with a "moderate but considerable" number of interrelated variables exhibit another essential feature, *organization,* undue to any source but the system itself.

Self-organization is a feedback-driven mechanism. As complexity is more frequent in those systems composed of a diversity of segregated agents under a large-scale integration overall (see figure 3), these will be more complex the more they acquire the *capacity* "to accommodate both specialized components that generate information and structured interactions that bind these components into a coherent whole"[13]. A complex system may be represented[14] with its components as the nodes and the interactions represented by the edges of an underlying graph[1]. The properties of statistically-significant sub-networks with nontrivial dynamics, –so-called dynamical motifs- can be understood as the building blocks of a complex networks' dynamics[15].

[1] A network topology constrains the system dynamics: it directs the flow of information, creates coherence patterns among selected agents and most interestingly to this work, shapes the emergence of a given macroscopic system state[13].

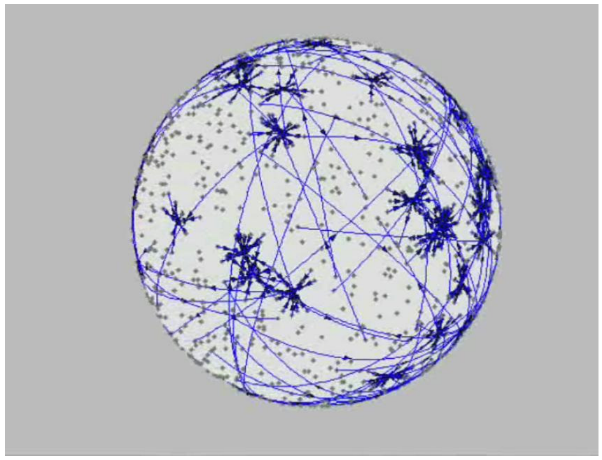


Figure 3. A small-world network is a compliant example showing both local and global agent coupling[c].

Perhaps it is this notion of *capacity* the stamp of the complex adaptive systems, where a sense of purpose defines a scale of fitness.

In brief, the self-organization found in some systems should be attributed to something other than an underlying set of basic equations to which it complies. In physics the latter has been traditionally the case, but in other sciences that is rather the exception. Advances in the study of complex systems from other sciences should enrich the set of methodologies to study matters of concern to current research in some of the physical sciences (e.g. condensed matter, finite systems, quantum information) and their boundaries with other disciplines.