Generation of Information and Complexity: Different Forms of Learning and Innovation

A Simple Mechanism of Learning

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What is the difference in evolutionary optimization of molecules, viruses, bacteria, plants, animals, and man? There are thousands of features in which the elements of the optimization process differ, in particular, the degree of complexity increases tremendously from molecules to man. The Darwinian principle of multiplication with inheritance, variation, and selection, however, applies to all of them. This is true despite the fact that the mechanistic details can be very different: RNA molecules and viruses are replicated by a complementary mechanism—the plus strand is the template for the synthesis of the minus strand and vice versa—bacteria and all other organisms duplicate their genetic material by means of direct double strand replication, and finally the higher species undergo a complex process of development from the fertilized egg to the adult organism. Inheritance of the genetic information for a repertoire of properties is an indispensable prerequisite and it exists in all the cases mentioned above. Needless to say, inheritance of properties in molecules is ridiculously simple compared to man. Variation is again different for the different systems and may be the result of simple mutation as in asexual species or a combination of recombination and mutation for sexual reproduction [1].[1] From the point of mechanistic details molecules and man have indeed very little in common. Selection, eventually, is again in action on the level of populations correcting the overshooting of growth by adjustment to the carrying capacity of the ecosystem.

The power of the Darwinian principle is its insensitivity to changes in mechanistic details. Otherwise, Darwin would have failed miserably in case the mechanism of inheritance mattered, because he believed most of his life in "panspermia" and therefore got this part of his concept completely wrong. In summary, Darwin's insight revealed a principle that operates on the population level and at the same

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TABLE 1

Comparison of Equivalent Notions in the Analogy between Evolution of Molecules and Foraging Ants

	Evolution of RNA	Foraging ants
Element	RNA nucleotide	Individual worker ant
Genotype	RNA sequence	Worker ant collective
Phenotype	RNA structure	Foraging path
Relation between elements	Mutation	Reorientation of path segment
Search process	Optimization of structure	Recruiting of food
Search space	Sequence space	Three-dimensional space
Random step	Mutation	Segment of ant walk
Self-enhancing process	Replication	Secretion of pheromone
Measure of activity	Mean replication rate	Mean pheromone concentration
Goal of the search	Target structure	Food source
Temporary memory	Sequence distribution	Pheromone trail
Learning entity	Population of molecules	Ant colony

time is largely insensitive to molecular details, because it counts progeny of species and their variants only.

How, if at all, is optimization related to the generation of information and "learning?" We consider a population of replicating molecules following Darwinian evolution. By change in the distribution of different variants the population adjusts to the environment [2]. Thereby it produces a kind of image of the environment in population structure, which can be visualized as a kind of cloud in an abstract space of sequences. Variation and selection induce changes into the cloud of sequences. Optimization of an RNA structure im-

plies gradual improvement of the environmental image on the sequence distribution and thus can be interpreted as

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a Darwinian "learning" mechanism on the population level. Computer simulations revealed many insights into this mechanism [3]. In particular, they showed that long epochs of little or no progress in the course of optimization are interrupted by short adaptive phases of fast progress. The population performs a random search through spreading in sequence space and when it found a sequence of higher fitness it starts a new adaptive phase taking it closer to the target, which is the optimal structure for the given purpose. Optimization in the example from evolution of molecules is tantamount to a population learning the best solution by trial-and-error. In this way the Darwinian mechanism generates information.

Now, we shall consider an entirely different example taking from swarm intelligence: ants foraging for food [4–6]. The individual ant performs like a random element and an individual trail to a food source is a particular solution to the foraging problem. In an analogy to optimization of molecules the ant corresponds to a single nucleotide and the ant trail to a particular RNA structure. It is interesting that the analogy can be extended to a great variety of details (Table 1) and this leads us to a similar conclusion as before: Molecules and foraging worker ants, for example, learn from their environments and they adopt a very similar strategy that operates on the level of an ensemble of elements. Both systems have memories, without which learning would be impossible: the mutant cloud containing previously selected molecules and the pheromone trail, and both memories are temporary and become extinguished after some time. Again we see the complexity of the individual does not matter. The ant and the nucleotide both fulfill the same rules in the learning mechanism.

What we have tried to illustrate here is just the simplest conceivable mechanism of learning. Without being able to go into details we remark that there exist many other strategies of learning. Let me address one example that is straightforward for illustrating the higher level of other forms of learning, neural networks. Again we have input, output, and also a kind of selection procedure imposed by a kind of learning rule. The nodes of the neural net, however, represent an ensemble with specific connections and this constitutes the higher complexity of the learning ensemble, whereas Darwinian 'learning' operates with independent elements: independently replicating molecules or independent ant workers laying down pheromone.

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[1] *In precise terms the Darwinian principle is an optimization heuristic rather then a principle or theorem. Optimization of fitness occurs independently of initial conditions only in some simple systems without mutation. The typical situation, however, is that the mean fitness is nondecreasing for most choices of initial conditions, whereas the start from special initial conditions may lead to decrease in fitness or even to non-monotonous behavior.*

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