The influence of learning on evolution

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April 21st, 1998

Abstract

In this seminar we will examine the article "The influence of learning on evolution" by Stefano Nolfi and Dominico Parisi. Learning and evolution are two complex processes which influence the development of individuals in a given population. The influence of evolution on learning is easily explainable in a Darwinian framework, but the opposite influence – that of learning on evolution – is less obvious. We will show that learning influences evolution even in a Darwinian framework (learned changes are not passed on to descendants), and that this influence has a beneficial effect. We will present two possible explanations of this effect.

1 Learning and Evolution

Learning and evolution are two processes which influence the development of individuals in a given population. These two processes work at different levels: evolution works on the population level – with each generation the population evolves and changes. Learning works on the individual level, with each organism learning and changing on its own. Moreover, evolutionary changes are generationally cumulative: each generation is built on all the previous generations. Learned changes are individually cumulative.

1.1 Influence of evolution on learning

The influence of evolution on learning can easily be explained in a Darwinian framework. Evolution shapes the genotype of the individuals, and this influences (directly or indirectly) the ways these individuals can act, interact with their environment and learn. Several experiments testing this influence have been made, and it has been shown that what is inherited is a predisposition to learn a task. That is, with each generation, the individuals in the population learn the required task faster. This predisposition to learn can manifest itself in many different ways, varying from the structure of the neural network to the initial weights of the net.

1.2 Influence of learning on evolution

The other influence, that of learning on evolution, is less easily explained in a Darwinian framework. After all, since learned changes are not passed on to the individual's descendants, it is not clear how learning can influence the way the population evolves. However, experiments performed by Hinton and Nowlan have shown such an influence to exist, and that if evolution must search for a very specific result among many useless alternatives, learning can aid this search.

In their experiments, random changes were introduced in the weights of neural networks during their 'life'. The result was an improvement in the evolutionary capabilities of these networks: fewer generations were required to reach the same results.

While the importance of these experiments is undeniable, they do have several limitations. The first is that in these experiments learning was equated with random change. Real learning, at least as we perceive it, is not random, but seems to have a direction, a goal. Moreover, learning is the result of an interaction between the creature and its environment. In these experiments no such interaction occurred (and indeed, there was no environment).

Finally, in these experiments the learning task and the evolutionary task coincide. There is no reason to assume that whatever an organism learns during its life will help its survival, yet this is exactly what was assumed here, and the organisms were chosen according to the success of their learning. One could claim that this equating of fitness with learning performance explains why learning influences evolution in these simulations.

In order to overcome these limitations, different simulations were performed by Parisi, Nolfi and Elman.

2 The simulations

In these simulations, organisms reproduce as a function of their performance in the task of capturing food present in the environment (evolutionary task). The organisms are modeled by neural networks living in an environment containing food. Each network has inputs encoding the location of the nearest food element relative to the organism. The network's output encode various possible motor actions that allow the organism to move and turn. The hidden layer in the network comprises seven neurons, and the network is fully connected.

During its life, each organism learns to predict how the position of food changes with its motor actions (learning task). This task, though it may be related to fitness, it conceptually distinct from the evolutionary task. In principle, an individual that learns quickly how to predict could have poor fitness and not reproduce, and a slow learner could have high fitness and reproduce.

In the experiments, a random population of 100 networks was generated, and each network performed 5000 steps in the simulated environment (food was periodically reintroduced). Afterwards, the 20 best networks were chosen, and each made 5 copies of itself, with 5 randomly chosen weights altered by a random factor of -1 to +1. The experiments were performed twice: once with a population that only evolved, and once with a population that both evolved and learned.

3 Results and analysis

It has been observed that in these conditions, learning has a positive influence on evolution. Populations that both evolve and learn exhibit a better growth of fitness across generations. Let us now try to understand why.

3.1 Exploring weight space

Let us imagine a multi-dimensional space which we will call *weight space*. If we have a neural network with n weights, we can imagine weight space to be a function $f : \mathrm{R}^n \rightarrow \mathrm{R}$, mapping each combination of weights to a fitness value. For our discussion, it will be better to imagine weight space to be a hyper-surface in R^{n+1}, with the 'height' representing the fitness.

In a population which only evolves, the decision as to which individuals should reproduce is only based on the fitness of the living organism. Learning, however, causes changes in weights. This means that the individual moves in weight space, and therefore, its total fitness is a function of the various fitnesses of the locations traversed during the organism's life. Since learning causes changes in the fitness of an individual, it can also influence evolution. And as we will now argue, it will *improve* it.

In a population without learning, the decision whether a given individual should reproduce, can only be based on the fitness of a single location in weight space (the individual's location). The region surrounding that single point remains unknown. The organism's offspring, however, will not be located at *exactly* the same point, but rather in its neighborhood.

Consider two individuals a and b, located in different regions of weight space, but having the same fitness. Let us assume that a is located in a local minimum (a 'valley') on the evolutionary surface, while b is located in a local maximum (a 'hill') on that surface. Evolution alone would have no reason to favor either a or b, but it is likely that offsprings of a will have higher fitness than offsprings of b.

Learning will allow evolution to find out about the regions in weight space surrounding the locations of candidates for reproduction. During life both individuals will move in weight space, and due to this movement the total fitness of a will be higher than that of b, so a will be chosen by evolution.

In other words, while evolution is based on the fitnesses of the currently living individuals, it would be more effective if it could be based also on the fitnesses of the offsprings of these individuals. Learning allows evolution to "look into the future".

It should be noted, however, that this argument is valid only for cases where reproduction is asexual. When reproduction is sexual, the offspring may be located in a different location of weight space than its parents, so it is not clear that exploring the regions where the parents are located will have any effect on evolution. Dominico and Nolfi are aware of this limitation, and say that the case of sexual reproduction should be investigated.

3.2 Dynamic correlation

The argument so far implies that even random movement in weight space during life can help evolution (which is in fact what Hinton and Nowlan demonstrated). But what about real learning?

In order to understand how learning affects evolution, we should consider two different hyper-surfaces in weight space. The *fitness surface* (which we have encountered before) represents the performance of each individual with respect to the evolutionary task, and the *learning surface* that represents the performance of each individual in the learning task. The position on the first surface determines which individuals will reproduce. Learning is directional, and tends to move individuals to higher places in the learning surface, so the learning surface determines how individuals will move in weight space. Since this movement influences the fitness of the individuals, learning has an influence on which individuals will be chosen for reproduction.

In these two surfaces are *statically correlated*, that is, if points have the same relative heights on the two surfaces, learning will always improve performance on the evolutionary task. This is what happens when the evolutionary task and the learning task coincide, but not in the general case.

However, even when the two surfaces are not statically correlated, there may be regions in weight space where *dynamic correlation* exists. In dynamically correlated regions, movements that result in increases in height with respect to the learning surface will cause increased heights on the fitness surface as well.

Let us now consider two individuals, a and b. Assume that individual a is located in a dynamically correlated region, while b is not. Learning will cause individual a to move up the learning surface, and since dynamic correlation exists, also up the fitness surface. Individual b, on the other hand, will also move up the learning surface, but not necessarily up the fitness surface. Therefore, individual a will end up with a higher fitness than his sibling, and will have more chances of being selected for reproduction. The final result is that evolution will have a tendency to select individuals which are located in dynamically correlated regions. Or, from a different point of view, learning represents an evolutionary pressure to select individuals which improve their performance with respect to the evolutionary task, due to learning.

Such an influence has indeed been observed in the simulations. Individuals of all generations learned to predict the influence of their actions on the position of the nearest food. If we examine how the ability to capture food changes during the life of the different individuals, we find that *on average*, individuals in generation 0 do not display an improvement in this ability. In later generations, however, the ability to capture food increases during life.

What happens is that in generation 0 individuals are randomly distributed in weight space. Some of them benefit from learning, and increase their food collecting ability, while other suffer from learning. On average, learning does not increase food finding ability. But as we have seen, learning guides evolution to select individuals who benefit from learning. In later generations, only (or mostly) individuals that are located in dynamically correlated regions survive, so learning improves the food finding ability of the whole population.

What can be inferred from this argument is that learning will have a beneficial effect on evolution no matter what the learning task is. However, in cases where the two tasks are less related, it can be expected that there will be fewer dynamically correlated areas in weight space, so the effect will be less strong. And in fact, Parisi and Nolfi report that in experiments in which the learning task was more complex, the effect was much weaker.

It should also be pointed out that in the experiments described here, some of the weights changed by learning directly influenced the food finding ability of the individuals. It remains to be seen whether this effect exists in more complex systems, where learning does not directly affect the performance in the evolutionary task.

4 Further research

As was already pointed out, reproduction in the simulations was asexual. The case of sexual reproduction may be different, and the article does not explain how learning will affect evolution in such a case.

In my opinion, the fact that learning *directly* affects weights in the neural network that determine the organism's behaviour (its performance in the evolutionary task) is also a serious problem. Real learning does not always have such a direct influence on behaviour. It remains to be seen what the effect of learning on evolution is in cases no such direct influence exists.

References

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[2] S. Nolfi, J.L. Elman, D. Parisi, *Learning and evolution in neural networks*, Adaptive Behavior, Volume 3, Number 1