In the last decade or so we have seen tremendous progress in Artificial Intelligence (AI). AI is now in the real world, powering applications that have a large practical impact. Most of it is based on modeling, i.e. machine learning of statistical models that make it possible to predict what the right decision might be in future situations. For example, we now have object recognition, speech recognition, game playing, language understanding, and machine translation systems that rival human performance, and in many cases exceed it (Hassan Awadalla et al. 2018; Hessel et al. 2017; Russakovsky et al. 2014). In each of these cases, massive amounts of supervised data exists, specifying the right answer to each input case. With the massive amounts of computation that is now available, it is possible to train neural networks to take advantage of the data. Therefore, AI works great in tasks where we already know what needs to be done.

The next step for AI is machine creativity. Beyond modeling there is a large number of tasks where the correct, or even good, solutions are not known, but need to be discovered. For instance designing engineering solutions that perform well at low costs, or web pages that serve the users well, or even growth recipes for agriculture in controlled greenhouses are all tasks where human expertise is scarce and good solutions difficult to come by (Dupuis et al. 2015; Harper et al. 2018; Hu et al. 2008; Ishida Lab 2018; Miikkulainen et al. 2018). Methods for machine creativity have existed for decades. I believe we are now in a similar situation as deep learning was a few years ago: with the million-fold increase in computational power, those methods can now be used to scale up to real-world tasks.

Evolutionary computation is in a unique position to take advantage of that power, and become the next deep learning. To see why, let us consider how humans tackle a creative task, such as engineering design. A typical process starts with an existing design, perhaps an earlier one that needs to be improved or extended, or a design for a related task. The designer then makes changes to this solution and evaluates them. S/he keeps those changes that work well and discards those that do not, and iterates. It terminates when a desired level of performance is met, or when no better solutions can be found—at which point the process may be started again from a different initial solution. Such a process can be described as a hill-climbing process (Figure 1a). With good initial insight it is possible to find good solutions, but much of the space remains unexplored and many good solutions may be missed.

Interestingly, current machine learning methods are also based on hill-climbing. Neural networks and deep learning follow a gradient that is computed based on known examples of desired behavior (LeCun et al. 2015; Schmidhuber 2015). The gradient specifies how the neural network should be adjusted to make it perform slightly better, but it also does not have a global view of the landscape, i.e. where to start and which hill to climb. Similarly, reinforcement learning starts with an individual solution and then explores modifications around that solution, in order to estimate the gradient (Salimans et al. 2017; Zhang et al. 2017). With large enough networks and datasets and computing power, these methods have achieved remarkable successes in recent years.

However, the search landscape in creative tasks is likely to be less amenable to hill climbing (Figure 1b). There are three challenges: (1) The space is large, consisting of too many possible solutions to be explored fully, even with multiple restarts; (2) the space is high-dimensional, requiring that good values are found for
Figure 1: Challenge of Creative Problem Solving. Human design process as well as deep learning and reinforcement learning can be seen as hill-climbing processes. They work well as long as the search space is relatively small, low-dimensional, and well behaved. However, creative problems where solutions are not known may require search in a large, high-dimensional spaces with many local optima. Population-based search through evolutionary computation is well-suited for such problems: it discovers and utilizes partial solutions, searches among multiple objectives, and novelty. (Image credit: http://deap.readthedocs.io/en/latest/api/benchmarks.html)

Evolutionary computation, as a population-based search technique, is in a unique position to meet these challenges. First, it makes it possible to explore many areas of the search space at once. In effect, evolution performs multiple parallel searches, not a single hill-climb. By itself such parallel search would result in only a linear improvement, however, the main advantage is that the searches interact: if there is a good partial solution found in one of the searches, the others can immediately take advantage of it as well. That is, evolution finds building blocks, or schemas, or stepping stones, that are then combined to form better comprehensive solutions (Forrest and Mitchell 1993; Holland 1975; Meyerson and Miikkulainen 2017).

This approach can be highly effective, as shown e.g. in the multiplexer benchmark problem (Koza 1991). Multiplexers are easy to design algorithmically: the task is to output the bit (among 2^n choices) specified by an n-bit address. However, as a search problem in the space of logical operations they grow very quickly, as 2^{2n+2^n}. There is, however, structure in that space that evolution can discover and utilize effectively. It turns out that evolution can discover solutions in extremely large such cases, including the 70-bit multiplexer (i.e. n = 6) with a search space of at least 2^{2^{70}} states. It is hard to conceptualize a number that large, but to give an idea, imagine having the number printed on a 10pt font on a piece of paper. It would take light 95 years to traverse from the beginning to the end of that number.

Second, population-based search makes it possible to find solutions in extremely high-dimensional search spaces as well. Whereas it is very difficult to build a model with high-order interactions beyond pairs or triples, the population represents such interactions implicitly, as the collection of actual combinations of values that exist in the good solutions in the population. Recombination of those solutions then makes it possible to collect good values for a large number of dimensions at once.

As an example, consider the problem of designing an optimal schedule for metal casting (Deb and Myburgh 2017). There are variables for number of each type of object to be made in each heat (i.e. melting process). The number of objects and heats can be grown from a few dozen, which can be solved with standard methods, to tens of thousands, resulting in billion variables. Yet, utilizing an initialization process and
operators customized to exploit the structure in the problem, it is possible to find good combinations for
them, i.e. find near-optimal solutions in a billion-dimensional space. Given that most search and optimization
methods are limited to six orders of magnitude fewer variables, this scaleup makes it possible to apply
optimization to entirely new category of problems.

Third, population-based search can be adapted naturally to problems that are highly deceptive. One
approach is to utilize multiple objectives (Deb et al. 2000): if search gets stuck in one dimension, it is
possible to make progress among other dimensions, and thereby get around deception. Another approach
is to emphasize novelty, or diversity, of solutions in search (Stanley and Lehman 2015). The search does
not simply try to maximize fitness, but also favors solutions that are different from those that already exist.
Novelty can be expressed as part of fitness, or a separate objective, or serve as a minimum criterion for
selection, or as a criterion for mate selection and survival (Cuccu and Gomez 2011; Gomes et al. 2015;
Lehman and Stanley 2010; McQuesten 2002; Mouret and Doncieux 2012).

For instance, in the composite novelty method (Shahrzad et al. 2018), different objectives are defined
for different aspects of performance, and combined so that they specify an area of search space with useful
tradeoffs. Novelty is then used as the basis for selection and survival within this area. This method was
illustrated in the problem of designing minimal sorting networks, which have to sort a set of \( n \) numbers
correctly, but also consist of as few comparator elements as possible (which swap two numbers), and as few
layers as possible (where comparisons can be performed in parallel). The search space is highly deceptive
in that often the network structure needs to be changed substantially to make it smaller. Combining multiple
objectives and novelty results in better solutions, and finds them faster, than traditional evolution, multiob-
jective evolution, and novelty search alone. The approach has already matched the minimal known designs
up to 17 inputs, and is now being extended to larger networks.

To conclude, evolutionary computation is an AI technology that is on the verge of a breakthrough, as
a way to take machine creativity to the real world. Like deep learning, it can take advantage of the large
amount of compute that is now becoming available. Because it is a population-based search method, it can
scale with compute better than other machine learning approaches, which are largely based on hill-climbing.
With evolution, we should see many applications in the near future where human creativity is augmented
by evolutionary search in discovering complex solutions, such as those in engineering, healthcare, agricul-
ture, financial technology, biotechnology, and e-commerce, resulting in more complex and more powerful
solutions than are currently possible.

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