Decision making on fitness landscapes

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HIGHLIGHTS

- Construction of multi-species model, single species landscape and system landscape.
- Monte-Carlo Step as model of decision making.
- Rational decisions do not lead to equilibrium.
- Mixture of local and global decisions produce better optimised systems.

ABSTRACT

We discuss fitness landscapes and how they can be modified to account for co-evolution. We are interested in using the landscape as a way to model rational decision making in a toy economic system. We develop a model very similar to the Tangled Nature Model of Christensen et al. that we call the Tangled Decision Model. This is a natural setting for our discussion of co-evolutionary fitness landscapes. We use a Monte Carlo step to simulate decision making and investigate two different decision making procedures.

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1. Introduction

Sewall Wright’s fitness landscape [1] posits that an individual’s reproductive success is a function of its genes. Under evolutionary pressure the genomes of a population shift to a peak on the fitness landscape where they remain until a higher fitness peak is discovered by a random mutation.

The idea has been used in theoretical evolutionary biology, e.g. in Kauffman’s NK model [2]. The same model has been used by Levinthal [3], Rivkin [4] and numerous others to study human organisations. To mention some of the early and highly cited work: Kauffman and collaborators worked on the idea of a technological landscape [5,6]; Ethiraj and Levinthal worked on organisational design landscapes [7,8]; Gavetti and Levinthal modelled cognitive search processes on landscapes [9].

The fitness landscape metaphor is powerful but difficult in many respects. The valleys assumed to separate fitness peaks may not exist in reality, peaks may be connected by selectively neutral ‘ridges’ [10]. Visualising high dimensional landscapes is hard and counter-intuitive [11]. However, the main issue for us is that the Malthusian fitness of an individual, intended as its ability to reproduce, should depend not only on the individual’s own genes but also on the populations of the other agents making up the eco-system. This is the viewpoint taken in the Tangled Nature Model (TNM) of evolution [12], which has been studied extensively as a model of biological ecologies [13–15] and which more recently has been extended to study systems.
of human organisations [16–18]. In these later works, evolution is by mutation and selection, as in biological systems. In this work, the TNM is enlarged by introducing agents which observe the dynamics while decisions regarding the fate of new mutants generated by reproductive errors are made ‘rationally’, towards increasing fitness. The resulting model, which we dub TDM for Tangled Decision Model, offers a new approach to discuss decision making based on faulty and/or incomplete information in an interacting, multi-species environment.

Consider the environment of a lemur. There are non-biological aspects like rivers and climate but one is forced to mention trees providing fruit and habitat, insects as prey and the fossa as a predator. These other species have environments whose description includes lemurs. Thus their fitness landscapes are intimately intertwined and changes by one species imply changing fitness values of the others along the genetic co-ordinates describing their mutual interaction e.g. as prey become better at evading predators the predator’s fitness decreases. A changing landscape means a changing selective difference between nearby points on the fitness landscape and new evolutionary paths can open as a result.

This notion of co-evolution is simply that species evolve together. This entails a continuous fluctuation and rearrangement of their fitness landscapes in response to the changes in the fitness and population of others. The same is clearly true when taking a sociological or economic view. Companies exist in a market with other companies, whose products they consume to make their own, which in turn are sold to other firms or to the general public. A change in the inputs or outputs of one company can clearly affect both suppliers and consumers. Consider refining ore. This industry uses the products of the mining and energy industries to produce metals which are sold to e.g. auto manufacturers, soft drink companies or jewellers. Development of a more efficient extraction technique or of a new lightweight alloy will have consequences for and change the ‘fitness’ of all the companies which supply or use products of a refinery.

Simple examples make clear that a one-to-one mapping of species, industry, organisation or agent to a single fitness value that is constant for all time is not realistic. Such a static landscape picture will only apply in the very restricted setting of one species in a constant environment or as an approximation for a very short timescale. In the traditional fitness landscape different species’ landscapes are unconnected and unaffected by the sizes of each other’s populations. The real fitness landscape seen by a single species should be continually shifting due to interactions with other species (as well as potential changes in the non-biological, regulatory or consumer environment). Evolution, either by rational agents attempting to increase their fitness or by blindly generated biological mutants, can move the species uphill, but can also cause the hill itself to shrink. By incorporating co-evolution the fitness landscape as usually envisioned is a metaphor stretched to its breaking point.

The dynamic nature of fitness landscapes has been explored before see e.g. [19] where the term ‘fitness seascape’ is used. This is a useful perspective but, in order to calm the seascape, we move up a level of description, from the landscape of individuals to a landscape of eco-systems. In this paper we construct a ‘system fitness landscape’ where every point represents an eco-system whose fitness is the sum of the fitnesses of all extant individuals. The higher this quantity, the more growth will occur and the system is said to be more ‘fit’. There is no competition or co-operation between different systems rather, as the individuals in a system grow, evolve, compete and co-operate, the system performs a walk in the system fitness landscape.

As mentioned, our TDM is in some respects identical to the well-studied Tangled Nature Model (TNM) of biological evolution [12]. The difference is the introduction of boundedly rational agents that try to optimise the fitness of their species by making ‘decisions’, while observing the model’s dynamics. The usual TNM agents will be dubbed ‘irrational’. We introduce two explicit decision making processes, local and global, and parameters controlling the degree of rationality. We then investigate co-evolution of both irrational and rational agents and how different decision making processes affect global optimisation.

### 2. Fitness functions

Let a species be specified by a genome $g$ consisting of $L$ binary variables. When we talk about species we have in mind both biological and economic species. In the latter, ‘species’ are organisations or products as spelt out in Section 3.1. The ‘population’ is to be thought of as size under some metric like number of employees or market share.

Consider first a single non-interacting species. A fitness function $f(g)$ takes genomes and returns real numbers. We then have another function $P$ taking fitness values and returning the probability, $0 < P(f(g)) < 1$, for that species to reproduce or grow during a certain time interval. We require $P$ to be monotonic so that $f(a) < f(b) \implies P(f(a)) < P(f(b))$. $P$ should also be a function of the population of the species, $N$, since there must be physical limits to growth. This implies that $P$ should be a sigmoid (s-shaped) function such as

$$P(g, N) = \frac{1}{1 + \exp(-f(g) + \mu gN)}.$$  \hspace{1cm} (1)

This form is not unique but serves our purposes. The damping term $\mu$ fixes the carrying capacity, i.e. smaller $\mu$ means that higher total population is possible.

Now consider a system of two species, labelled 1 and 2 with populations $N_1$ and $N_2$. Species 1 has a fitness $f(g_1; g_2, N_1, N_2)$ depending on the other species present as well as its population. $P$ has the same form as before

$$P(g_1; g_2, N_1, N_2) = \frac{1}{1 + \exp(-f(g_1; g_2, N_1, N_2) + \mu N)}$$  \hspace{1cm} (2)

with $N = N_1 + N_2$ and we have assumed that $\mu$ is constant across species so they all use the same amount of ‘resources’.
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