Evolvability in Developmental Systems

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The developmental mapping from genotype to phenotype is responsible for much of the evolvability (adaptive variation) exhibited in nature (Raff 1996; Kirschner & Gerhart 1998; Wagner & Altenberg 1996). Random mutations are transformed into structured phenotypic variation and the effects of deleterious mutations are mitigated. This mechanism is powerful precisely because search becomes constrained, generating only highly adaptive phenotypes. In evolutionary computation, acquiring such constraints and bias is akin to learning the underlying structure of a particular fitness function; such structure can be exploited to improve search efficiency. For example, when evolving a design for a coffee table, an evolvable encoding would discover that table height and surface area correspond to fundamental axes of variation, constraining search to solutions that maintain constant height and high surface area (Hornby 2004). Such evolvability is exhibited in indirect encodings, particularly developmental systems.

Evolvability helps find good "trajectories" through the search space, not just good fitness peaks. However, selection for evolvability is not always possible with many fitness functions; in general evolution is opportunistic, and will take large immediate fitness gains over smaller fitness gains that may lead to better (e.g. more evolvable) parts of the search space. Thus selecting for evolvability and selecting for good solutions can be viewed as generally antagonistic goals. In other words, even when using developmental encodings, *there may be no real selection pressure to optimize the genomic representation for evolvability*. This observation may help explain in general why in some cases developmental encodings do not perform well when compared to simpler direct encodings (Reisinger & Miikkulainen 2006).

One way in which a consistent selection pressure for evolvability can be generated is by systematically changing the fitness function over time (Kashtan & Alon 2005). However if the representation itself is not adaptable, as in the case of direct encodings, this selection pressure is ignored, leading to highly-optimal, but "brittle" solutions. We believe that this phenomenon may be responsible for much of the cycling and disengagement behavior seen in competitive coevolution; since direct encodings cannot store information about search, populations may be prone to "forgetting" past strategies if they are no longer required to beat the opponent population.

In order to maximize evolvability, representations should be constructed in such a way that phenotypic variation can be adapted to match the structure of the fitness function in as few mutations as possible (i.e. maximize the detectability of mutations affecting phenotypic variation (Reisinger & Miikkulainen 2006)). More mutations requires a correspondingly larger selection pressure to be tenable. Thus, in order to be maximally evolvable, representations must be able to adapt the genotype-phenotype mapping at all levels, ranging from fundamental design changes to small phenotypic tweaks, using as few mutations as possible. Developmental systems allow for this kind of adaptation implicitly through overlapping gene expression domains (Davidson 2001; Raff 1996):

1. Mutations can affect both fundamental structure (early development), and fine tuned structure (late development).
2. Expression domains can be easily copied between genes.
3. Upstream mutations cause expression domains to shift.
4. Weak-linkage allows mutations to be made without affecting other processes (linkage is under genetic control).

Initially, the representation is not canalized, and thus does not guard against deleterious mutations. However, as evolution progresses, the representation acquires evolvability with respect to the fitness function and structural changes are made to increase the adaptivity of mutations.

One important task for developmental systems research is to determine what functional benefits of development cannot be captured in simpler indirect encodings. For example, it is clear that simple indirect encodings are capable of structuring phenotypic variation, at least under certain fitness regimes, thus evolvability is not unique to developmental systems. On the other hand, spatial patterning and reuse with variation seem to be features that can only be realized using developmental semantics. Determining specifically the benefits of development is important because developmental systems are computationally expensive; thus, they should only be applied in cases where their specific strengths are most beneficial. It is our opinion that developmental systems show the most promise for search problems that are currently intractable, and furthermore may prove to be inefficient in simple benchmark problems.

Using a developmental system, search bias can be adapted over the course of evolution, and therefore such systems can become more evolvable towards a specific fitness function. However, they will only do so if there is sufficient selection pressure. Thus, the interplay between representation and fitness function must be considered when designing evolvable developmental encodings. We are currently investigating how developmental systems can be made more evolvable, focusing in particular on:

1. What mechanisms can ensure selection pressure for evolvability?
2. How can selection for evolvability be balanced with fast, exploitative search?
3. In what domains is evolvability necessary?
4. What representational features allow populations to acquire evolvability over time?
5. How can developmental systems be simplified without reducing their overall evolvability?

Ultimately this work will lead to more powerful encodings capable of solving complex optimization and design problems.

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