Exploiting Morphological Conventions for Genetic Reuse

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There is a growing consensus among researchers in evolutionary computation that the discovery and separation of genetic modules can make complex structures easier to evolve by restructuring the genotype-phenotype map, and also by allowing genetic material to be reused [1]. Many such systems follow the philosophy that effective reuse can be achieved by first discovering or building useful modules, and then duplicating them in the phenotype after they have been discovered [2–4]. We believe that that duplication of genetic modules is not the primary evolutionary factor leading to reuse of phenotypic structures. Instead, natural evolution first establishes a *morphological convention*, such as bilateral symmetry, and then exploits that convention as a framework for repetition of phenotypic features.

A genetic encoding that can reuse genes typically can specify where in the phenotype a particular genetic module is to be located. A common method for achieving reuse is to add new instantiations of the same genetic module, thereby duplicating its presence in different locations of the phenotype. While such an approach does achieve reuse, it also suffers from several limitations. For example, in Modular NeuroEvolution of Augmenting Topologies (Modular NEAT), neural modules that evolve independently are combined to form complete networks [2]. While reuse of modules in Modular NEAT was shown to be more effective than a direct encoding without reuse, the ability to copy a module anywhere in the genotype discourages specialization. In addition, even when specialization occurs, solutions tend to be brittle because slightly changing the placement of a module can radically alter or even destroy functionality. Even systems with developmental encodings [5–7] suffer from the problem that small genetic changes can irreparably alter the phenotype by causing an entire module to appear in an inappropriate location. In addition, when duplicated modules are identical in all locations, the system cannot benefit from reuse with variation, which is seen throughout nature: limbs, digits, and spinal segments all display common themes repeated with slight variation [8, pages 30-31].

In contrast, natural evolution frequently discovers duplicate modules *simultaneously*. For example, legs evolved at the same time, as opposed to one leg evolving alone and then being copied onto the other side of the body [9, p. 49]. In other words, the two arms, two hands, two eyes, and two ears all owe their duplication to a previously established morphological convention of bilateral reuse [9,

p. 115]. Similarly, the spinal segments are aligned with a preexisting convention of body segmentation, which even preceded the vertebrates [9, pages 189-190]. That is, a single spinal segment "module" was not first discovered once and then duplicated over generations several times. Nature establishes such conventions developmentally through *morphogenetic fields*, i.e. modular substructures in the developing embryo that are identified through the presence of specific protein concentrations [10] .

The divide-and-conquer approach of the engineer, wherein a problem is broken down into parts that are then assembled into a final product, is frequently not the approach of natural evolution. Instead of discovering, as an engineer, what parts may be necessary to assemble an artifact, a practitioner of evolutionary computation instead might ask: Is there a preexisting schema (perhaps associated with a different but related artifact) in which conventions are already established that are desired in the final product? For example, while an engineer might begin designing an airplane by deciding how to build wings, tiles, and wheels, the evolutionist might consider instead that there is already a vehicle schema (such as a carriage or automobile), that shares many conventions with an airplane, and thus may serve as a starting point from which to make those elaborations necessary for flight. It is an unusual way of thinking, but it may be necessary, since evolution is not necessarily a competent engineer.

Therefore, our position is that an effective way to evolve complex structures is through a developmental encoding in which robust morphological conventions can emerge [11]. However, so far artificial developmental systems do not match nature's ability to establish and maintain a convention of reuse long enough for it to be significantly exploited. Establishing such a capability is a critical milestone on the path to automated modular discovery of complex structures.

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