Genetic and Environment-Induced Innovation: Complementary Pathways to Adaptive Change that are Facilitated by Degeneracy in Multi-Agent Systems

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Extended Abstract

Understanding how heritable and selectively relevant phenotypes are generated is fundamental to understanding evolution in biotic and artificial systems. With few exceptions (e.g. viral evolution), the generation of phenotypic novelty is predominantly discussed from two perspectives. The first perspective is organized around the concept of fitness landscape neutrality and emphasizes how the robustness of fitness towards mutations can facilitate the discovery of heritable adaptive traits within a static fitness landscape (Wagner 2008).

A somewhat distinct perspective is organized around the concept of cryptic genetic variation (CGV) and mostly emphasizes the importance of particular population properties within a dynamic environment (Gibson and Dworkin 2004). CGV is defined as standing genetic variation that does not contribute to the normal range of phenotypes observed in a population, but that is available to modify a phenotype after environmental change (or the introduction of novel alleles). In short, CGV permits genetic diversity in populations when selection is stable yet exposes heritable phenotypic variation that can be selected upon when populations are presented with novel conditions. Both pathways to adaptation (genetic and environment-induced phenotypic variation) are likely to have contributed to the evolution of complex traits (Palmer 2004) and theories of evolution that cannot account for both pathways are either fragile to or reliant upon environmental dynamics.

Here we use requirements from these pathways to evaluate the merits of a new hypothesis on the mechanics of evolution. In particular, Gerald Edelman has proposed that degeneracy – the existence of structurally distinct components with context dependent functional similarities – is a fundamental source of heritable phenotypic change at most/all biological scales and thus is an enabling factor of evolution (Edelman and Gally 2001) (Whitacre 2010). While it is well-documented (and intuitive) that degeneracy contributes to trait stability for conditions where degenerate components are functionally compensatory (Whitacre and Bender 2010), Edelman argues that the differential responses outside those conditions provide access to unique functional effects, some of which can be selectively relevant given the right environment.

We recently reported evidence that degeneracy supports the first pathway by creating particular types of neutrality in static fitness landscapes that can increase mutational access to heritable phenotypes (Whitacre and Bender 2010), and fundamentally alter a system's propensity to adapt (Whitacre et al. in press).

Using models from (Whitacre et al. in press), here we present findings that degeneracy within evolving multi-agent systems may create characteristic features of CGV at the population level; thereby allowing the model to also exploit an environment-induced pathway to adaptation. In particular, we show that for static environments, degeneracy facilitates high genetic diversity in populations that is phenotypically cryptic, i.e. individuals remain similar in fitness (Figure 1). When the environment changes, trait differences across the population are revealed and some individuals display a phenotypically plastic response that is highly adaptive for the new environment. These CGV features are not observed in populations when degeneracy is absent from our model. We discuss the theoretical significance of a single mechanistic basis (degeneracy) for complementary pathways to adaptation.
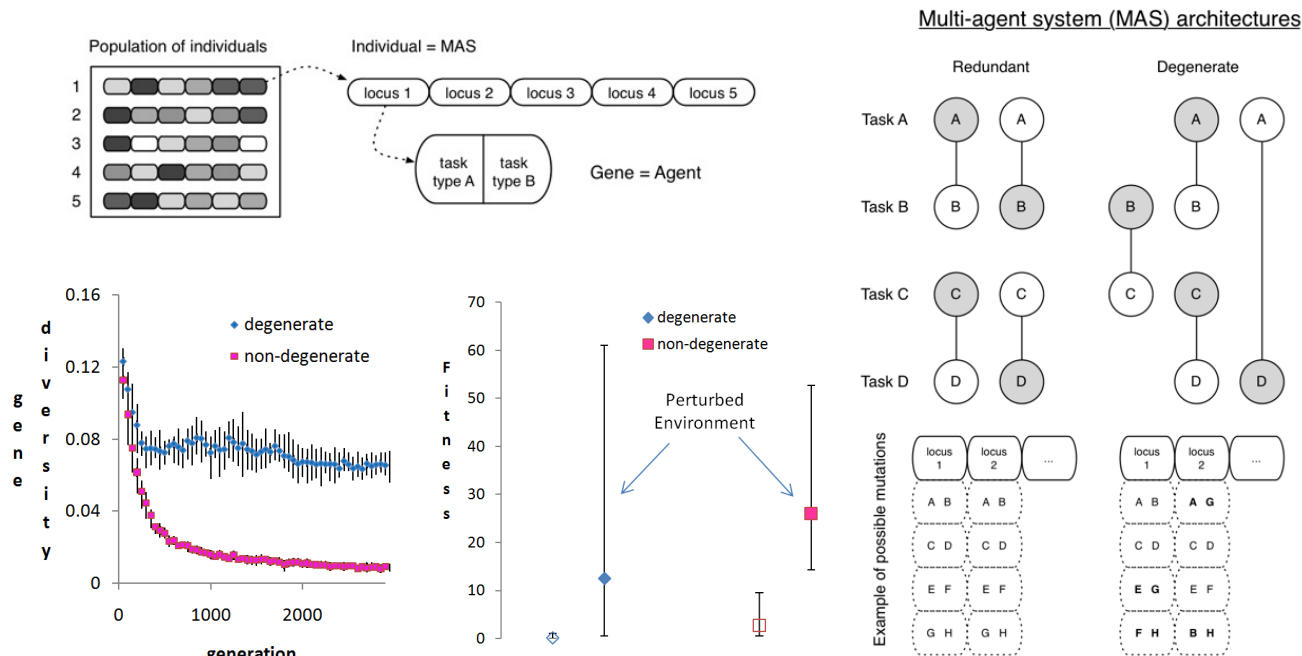
Figure 1: Top-Left Panel) Multi-Agent System (MAS) encoded within a genetic algorithm. Agents perform tasks to improve MAS fitness in its environment, see (Whitacre et al., in press). **Top-Right Panel**) Illustration of genetic architectures for degenerate and non-degenerate MAS. Each agent is depicted by a pair of connected nodes, with the two nodes representing two types of (genetically determined) tasks that the agent can perform. **Bottom-Right Panel**) The number of task type combinations (alleles) possible in a degenerate MAS is larger than non-degenerate MAS so it is necessary to artificially restrict experiments to similar genotype space sizes as illustrated here; for more details see mutation operator description in (Whitacre et al., in press). **Bottom-Left Panel**) Genetic diversity (Hamming distance in genotype space between population members) plotted over 3000 generations of evolution within a static environment. **Bottom-Middle Panel**) Fitness of population members at generation 3000 is recorded and then reevaluated within a moderately perturbed environment. In these results, we observe high genetic diversity in the degenerate population that is cryptic (negligible fitness differences) within the stable environment, but that is released/exposed when the same population is presented with a new environment. Some of the observed plastic phenotypic responses are found to be highly adaptive in the new environment. CGV was largely absent in the evolution of non-degenerate MAS, even when environments are modified to increase mutational robustness (not shown). Optimal fitness = 0 for original and perturbed environments.

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