Evolution-Inspired Approaches for Engineering Emergent Robustness in an Uncertain Dynamic World

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Extended Abstract

Engineering involves the design and assemblage of elements that work in specific ways to achieve a predictable purpose and function. In systems design, engineering takes a conceptual "top-down" approach to problem solving that aims to decompose a complicated problem into separable and more manageable sub-problems. While this strategy has been successful in designing systems that deftly operate under predetermined conditions, these same systems are often notoriously fragile when conditions change unexpectedly.

In contrast, biological systems operate in a highly flexible manner with no pre-assignment between components and system traits. Instead of relying on the prediction of future environments, biological systems (e.g. immune systems, cell regulation) quickly learn/explore appropriate responses to novel conditions and inherit new routines to remain competitive under persistent environmental change.

Taking examples throughout biology, it has been proposed that degeneracy - the existence of multi-functioning components with context-dependent functional similarity - is a primary determinant of biological flexibility and a key differentiating factor in the robustness and evolvability of designed and evolved systems (Edelman and Gally 2001) (Whitacre 2010) (Whitacre and Bender 2010) (Whitacre and Bender 2010). Degeneracy is routinely eliminated in engineering design and its role in the robustness of biological traits is well-documented, however the influence that degeneracy might have on the flexibility of engineered and artificial systems has only begun to be investigated (Whitacre et al. in press).

Here we present evidence (Figure 1) that degeneracy enhances the robustness and evolvability (i.e. the rate and magnitude of heritable adaptive change) of multi-agent systems (MAS) that are taken from (Whitacre et al. in press) and modified to more closely reflect systems engineering problems subject to heterogeneous and unpredictable environments. First, we find degeneracy can increase MAS robustness toward a set of environments experienced during the MAS lifecycle. When robustness is important to fitness, we also find degeneracy can be selectively (not only passively/neutrally) acquired. However, and unbeknownst to myopic selection, this acquisition of degenerate robustness ultimately promotes faster rates of MAS design adaptation when the environment changes dramatically (at generation 3000, Figure 1), i.e. evolvability has been indirectly enhanced through the selection of degenerate forms of robustness. In contrast, robustness and evolvability are lower in MAS comprised of multi-functioning agents that are never degenerate, i.e. agents do not exhibit partially overlapping functionality but instead are either identical or completely dissimilar to other agents. In a forthcoming article, we further show that many of these findings can be reversed if environments are simplified and decomposable, i.e. environments show little variability during the MAS lifecycle and those environmental variations that are experienced are separable/modular.

In presenting these findings, we discuss how degeneracy might lead to new prescriptive guidelines for complex systems engineering: a nascent field that applies Darwinian and systems theory principles with the aim of improving flexibility and adaptation for systems that operate within volatile environments. We propose that versatile and functionally similar agents/sub-systems/software/vehicles/machinery/plans may sometimes dramatically improve a system's robustness to unexpected environments in ways that cannot be accounted for by economic portfolio theory.

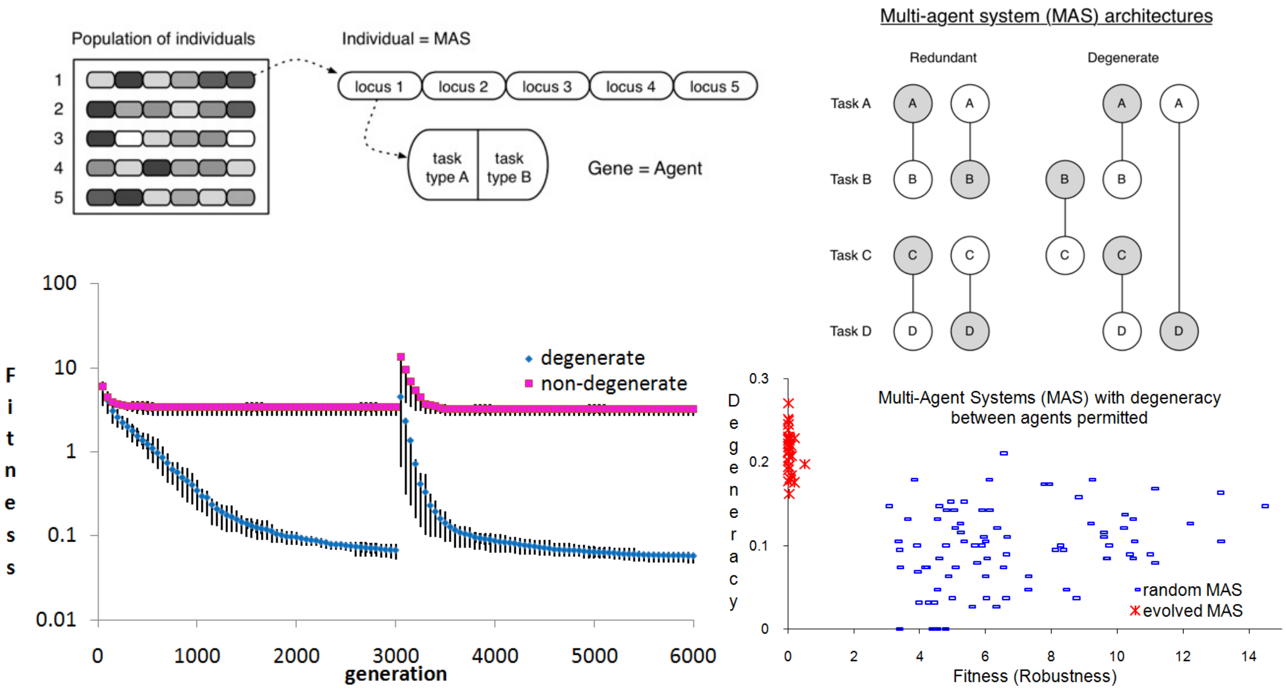

Figure 1: **Top-Left Panel**) Multi-Agent System (MAS) encoded within a genetic algorithm; for details, see (Whitacre et al. in press). Agents perform tasks to improve MAS fitness in its environment. **Top-Right Panel**) Illustration of genetic architectures for degenerate and non-degenerate MAS. Each agent is depicted by a pair of connected nodes, with the two nodes representing two types of (genetically determined) tasks an agent can perform. Models are adapted from (Whitacre et al. in press) to reflect a systems engineering context that is to be fully described in a forthcoming article. Differences in modeling conditions, compared with (Whitacre et al. in press), include: larger MAS (120 agents), each agent takes on more tasks during its interaction with the environment (20 tasks), agent behaviors are simulated using an unordered asynchronous updating scheme, environments are defined by more types of tasks (20 types, 48000 tasks in total), and new constraints in function combinations within each agent (to be described in forthcoming paper). **Bottom-Left Panel**) Evolution of MAS Fitness under one set of environments and then (at gen. 3000) evolution continues under a new set of environments. Optimal fitness = 0 for both original and new environments. Within the new environments, degenerate MAS appear to evolve more quickly while non-degenerate MAS evolve somewhat more gradually. **Bottom-Right Panel**) Degeneracy and fitness calculations for MAS in which degeneracy is permitted. Results show MAS evolved under random selection and MAS evolved to be robust within the environment. Here we see selection has increased degeneracy levels in the MAS (reported results are taken immediately after the first 3000 generations of evolution).

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