

Keck program statement for  
"Evolution of Complex Structure and Form"

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It is useful to distinguish two broad kinds of change in evolution: the change of frequencies of extant phenotypes and the change of phenotypes themselves, that is, their innovation. The former kind of change is the domain of natural selection. The second kind of change is about novelty or "the origin of variation", as biologists call it. The study of population dynamics is concerned with the first type of change and benefits from a well developed theoretical framework. In contrast, no comparable framework (conceptual or formal) exists for addressing the origin of phenotypic variation. This is a central and vexing problem in our understanding of evolution. Natural selection does not explain novelty, nor does genetic variation per se, since random genetic mutations have non-random phenotypic consequences. The fact that evolution tinkers does not imply that the set of possible biological entities is a pile of cards, each of which can be picked at random. A biological organization--any organization--channels change or innovation in specific (not necessarily deterministic) ways, and therefore induces a notion of "neighborhood"--the set of organizations attainable from here with processes available now. The issue of whether (and how) B can be obtained from A logically precedes the issue about the fate of B in a population. The study of selection dynamics illuminates the conditions on the "invadability" of a population by B, but it hardly illuminates the conditions on the "attainability" of B. This attainability derives from the internal constitution of entities. Which transitions in evolution count as "major" can be argued only on the basis of an understanding of the variational properties of molecular and cellular organizations. This is broadly what we mean by the Keck program component labelled "evolution of complex structure and form": a focus on the emergence of organizational structure with the aim of understanding its variational properties.

Clearly, such an analysis begins with a stance about what a biological object is. There are many possible levels of abstraction, but one common ground that supports the unusual teaming up of a social scientist with a chemist is the view of organizations as networks: social and molecular networks as regulated flows arising from the interaction of agents. In chemistry agents are molecules, and "flows" can be viewed as pathways of chemical transformation and/or of signal transduction. In social networks agents are people or firms, and "flows" are multiple social and economic exchanges among them. The basic instinct of our collaboration is that organizational agents, instead of being sharply bounded objects, are nodes or sites in (multiple) regulated and

coordinated flows. "Emergent organizations", in this view, are various modes of coordinating and "stapling" together multiple self-maintaining flows, at both the agent and the system levels.

To understand the origin of organizational structure, that is, of the patterns of regulation and coordination in such networks, we propose a focus on "heterarchy". Heterarchy emphasizes the engagement of the same set of agents in multiple concurrent and cross-cutting networks. The cross-cutting aspect is of interest because it is a potential source of conflict, and hence of pressure to integrate or separate, that is, to reorganize. The work of John Padgett and David Stark, for example, evidences that heterarchy is a fact of social and economic systems, and that it is at the core of variational properties of organizations. Heterarchy (although under a different name) is coming to be recognized as the next software crisis, and is triggering interesting ideas in programming language constructs (the equivalent of "institutions" or schemes of flow regulation) for distributed systems. Oddly, it seems that the concept of heterarchy has not guided much of evolutionary reasoning in molecular biology.

Conditions for heterarchy are inherent in distributed systems, even when they are designed. Stated abstractly, heterarchy arises when components or agents interact with different laws of composition at the same time. Each mode of interaction gives rise to a particular network topology and its dynamics. When agents are capable of more than one mode of interaction the same agents end up participating in different components simultaneously. (One example in politics is "multivocality".) If they must coordinate to sustain the overall system, we say they cross-cut (component boundaries).

Instances of cross-cutting arise in distributed programming systems when the flows generated by communication, synchronization, and partial failure handling do not align with the logic of component functionality (inheritance relation, "uses" relation).

One example in the social arena is provided by Padgett's account of the evolution of Renaissance Florentine banking, in which constitutive families participated simultaneously in networks of social, economic, and political relations, which controlled one other. Other examples are the post-Communist work teams and economic organizations in Hungary, studied by David Stark. To be successful, these must participate simultaneously in markets and in patronage systems.

Cross-cutting networks in molecular biology are, for example, signal transduction pathways, such as mating, filamentation and HOG (osmolarity) in yeast that share several components. At the origin of multifunctionality is sharing in general--of

resources, transport routes, join points of control, or end products and intermediate of synthesis pathways. These generate ample opportunities for cross-cut, the actual form of which shapes the future coevolution of the network components with the patterning of their interconnections.

In programming, cross-cut is at the origin of "tangled code" [ref]. The Rube-Goldberg appearance of molecular organization in biology could be the molecular version of tangled code, but it could also be the expression of still-to-be-understood organizational principles that have arisen in evolution to control the entanglement deriving from cross-cut. Issues surrounding the "evolution of evolvability" could be framed in such terms.

The heterarchy view of organizations suggests a phylogeny of flows to complement a phylogeny of components: the evolution of banking to go with the evolution of banks. One response to coordination conflicts and pressures might be evolution at the level of interconnection across flows, more than innovation at the level of components. Such rewiring of connections among flows might further cascade into tipping the self-maintaining flows themselves from one dynamic basin of attraction to another. Reconnecting banking into politics, for example, might radically change (intentionally or not) banking itself. The heterarchy view also suggests that traditional hierarchies (seen as partial orders, not necessarily trees) are a highly derived organizational structure that needs to be explained, and whose potential for innovation rests on some unavoidable foundation of cross-cutting heterarchy. To continue with the social example, the Renaissance conception of the autonomous individual might itself be rooted historically in a particular configurational nesting of politics, economics, and social networks.

One central open question for us is the meaning of "institution" in the molecular as well as in the social domains. A particular type of "cross-cutting flows" of great interest both in chemistry and in the social sciences is the interleaving of regulatory (and informational) networks through production networks of action-reaction metabolism. Padgett has discovered in his empirical studies of Florentine banking that the "logic of banking", at the level of economic rules and roles, is anchored by a "logic of identity", at the level of persons and careers, which both connects banking into the rest of the society and helps to reproduce particular market structures through regulating the recombination of people into banks. At the level of system, these "logics of identity" (family, guild, social class, etc.) act as translation protocols, permitting the economic sector to "talk to" or "compute with" the political one. The banking speciation question then becomes what historical forces and explosions "rekey" this economic-political interface from one logic-of-identity to another.

Fontana is just starting new research on signal transduction pathways that will probe analogous issues in molecular chemistry. "Institution" is an unfamiliar word in chemistry, but surely the regulatory networks and protocols that word implies are of central importance in chemistry. At very least, an effort to try to operationalize a "linguistics" for chemistry might prove provocative.

The first step in our Keck program effort to develop such themes will be for Fontana and Padgett to write jointly a programmatic paper, a "manifesto" if you will, developing the plausibility and arguing for the promise of these heterarchy ideas, using historical social networks, cellular molecular biology, and distributed computation as focused examples for comparison. After the joint paper, we will supplement ourselves through assembling a small workshop or possibly month-long research group of researchers in a variety of substantive fields, all of whom, in our view, are interested in "heterarchy" ideas, whether or not they use that word. An edited book would be an ideal outcome, but it is too early to precommit ourselves to that goal at present.

A further goal is the development of a possibly formal prototype model of heterarchy and its impact on evolutionary dynamics and the origin of organizational structure. Extant systems, such as AlChem, could be diverted from their original scope to model such issues. Implementing multiple laws of interaction aside from functional application is very easy.