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Mini-review

From genes to phenotype: dynamical systems and evolvability

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The advent of genetics as an autonomous field of inquiry is closely associated with the establishment of the concepts of genotype and phenotype (Sapp, 1983). Heritable variation is generated at the genotypic level. Mendelian laws specify how this variability is transmitted to the next generation while selection operates at the level of gene product, i.e., the phenotype. The definition of this conceptual genotype-phenotype dichotomy allowed, for example, the integration of Mendelian genetics and population dynamics; a powerful tool of analysis which has been at the core of the Neo-Darwinian Synthesis (e.g. Provine, 1971; Mayr & Provine, 1980). A consequence of the consolidation of this conceptual framework was the effective elimination of development from the corpus of theoretical evolutionary biology.

In the theoretical scheme proposed by evolutionary genetics, development is the function that maps the genotype onto the phenotype. It is well known that, even at the lowest levels of protein transcription, the relationship genotype-phenotype is not one-to-one. At higher levels of interaction, such as morphological traits, the genotype-phenotype is more complex and non-linear. For such a reason, genetic theory has to postulate *ad hoc* properties, such as pleitropy, penetrance, covariance, etc. to deal with the non-linear interactions characteristic of developmental systems (Cheverud, 1984). This phenomenological treatment, although satisfactory when studying the dynamics of gene transmission and evolution, prevents the possibility of studying the role of development in evolution.

These non-linear interactions at the molecular, cellular and tissue levels give a structure to developmental systems that may have important evolutionary consequences. In particular, I would like to review the mathematical properties of the genotype-phenotype mapping function, explore its emerging properties and relate them to the issue of opportunity and constraint in morphological evolution. I will conclude with a speculative hypothesis on the role of selection at the level of the dynamical properties of generative systems.

The mapping of genes to phenotype

There are two ways to conceptualize the relationships between genes, development and phenotype (Fig. 1). Since the discovery of genes as the units of heredity, there has been a tendency to view genes as the determinants of form. Genes control developmental processes, which in turn, generate form (Fig. 1a). If this hierarchical scheme were correct, both morphological evolution and development could be reduced to purely genetic problems. This is reflected in the positions of some evolutionary geneticists who view evolution as a change in gene frequencies, or, in the molecular biologist's view of development as a temporal and spatial sequence of gene expression.

This depiction of genes and development as independent levels is incorrect in the sense that genes do not specify development, or even form, because gene action itself is intimately linked to developmental interactions. This interactive nature of developmental processes is illustrated in Fig. 1b. Genes make proteins that either regulate the expression of other genes, or in the case of products of the so-called morphogenetic genes (e.g. Edelman, 1988), determine morphogenetic properties such as extracellular matrix composition,

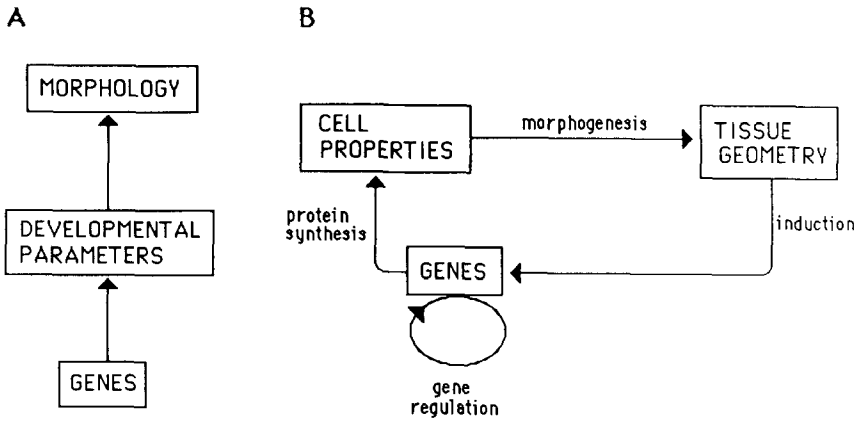

Fig. 1. (A) A hierarchical scheme of the genesis of form with genes as the controlling agents; — (B) Cyclical view of development in which genes are just one step in the chain of interactions. In this case, gene expression is both the cause and the effect of a morphogenetic process.

cell adhesion, mitotic rate, diffusion constant, kinetic activity, etc. Morphogenesis is the result of complex physico-chemical interactions at this level. One of the outcomes of morphogenetic processes is that the spatial relationships among cell populations are altered. Often, a so-called inductive event occurs when populations of cells with different developmental histories are suddenly juxtaposed as a result of a morphogenetic process. Induction implies that the expression of some genes is repressed while a new set is turned 'on'.

The implications of this cyclical/feedback scheme drastically alter our perception of how complex morphologies evolve. Development cannot be reduced to a problem of gene expression, since gene expression itself is under epigenetic control (Alberch, 1989). Therefore, although gene frequencies are a valid method for evolutionary 'bookkeeping' (see Wimsatt, 1980; Sober & Lewontin, 1982), we cannot have a purely genetic theory of morphological evolution. Such a theory of evolution of complex morphologies has to be based on the global properties of the network of interactions that characterize development (Fig. 1b).

Developmental dynamics and pattern formation

Morphology (pattern) is the result of the set of genetic and developmental interactions discussed above. It is essential to realize that these interactions have properties that emerge from the dynamics of the system and

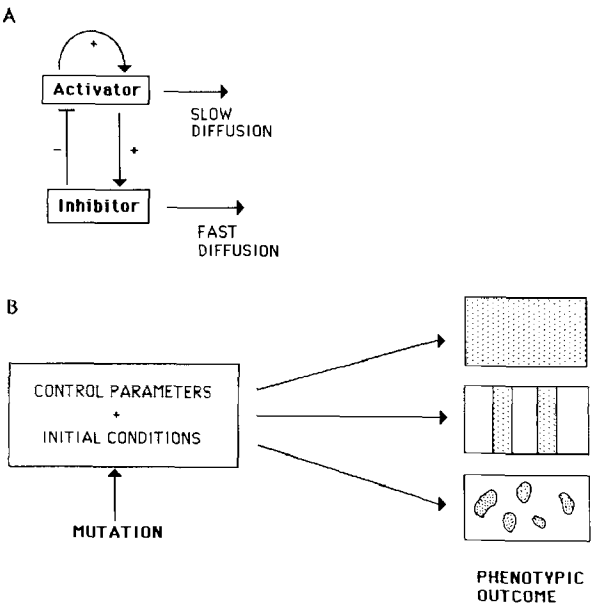

Fig. 2. (A) The simplest pattern formation mechanism is an activator-inhibitor system of interaction which consists of a slow-diffusing 'Activator' that induces the production of the 'Inhibitor' which diffuses relatively faster than the 'Activator'. The 'Activator' induces the production of the 'Inhibitor', which in turn breaks down the 'Activator'. Such a system can generate stable spatially-heterogenous patterns of chemical distribution; - (B) Genetic mutation can affect the values of control parameters, such as diffusion rate and kinetic activity, as well as initial conditions. Quantitative regulation of these morphogenetic values can generate qualitative different phenotypic outcomes, such a uniform, 'stripped' or 'spotted' patterns of chemical distribution (e.g. Murray, 1981).