Dissociation and Heterochrony

In 1770, Daines Barrington, an English jurist and general scholar, published a paper in the *Philosophical Transactions of the Royal Society*\(^{(1)}\) entitled: ‘Account of a very remarkable young musician.’ He wrote of the visit to England, six years previously, of a prodigy named Johannes Chrysostomus Wolfgangus Theophilus Mozart. (Remember that Mozart, during his English visit, was an untested and puzzling eight year old curiosity, not yet a principal icon of human achievement.)

Two aspects of young Mozart, united by the single theme of dissociability, particularly intrigued Barrington. First, he marvelled that musical talent could be so mature and refined in a young boy, otherwise so typically childish. The musical faculty must be a separable component of mental ability. Secondly, he asked Mozart to sit at the harpsichord and improvise compositions expressing the single emotions of love and rage. Mozart’s immediate and consummate success convinced Barrington that the whirligig of human emotional life must be dissectable into separate essences.

This theme of dissociation into separate modules, each subject to largely independent manipulation and alteration, lies at the heart of any hope for resolving the natural development (ontogeny or phylogeny) of any complex system, biological or otherwise. Indeed, the first great argument against the possibility of evolution — Cuvier’s correlation of parts — was rooted in a denial of dissociability. In his *Discours préliminaire*\(^{(2)}\) of 1812, Cuvier portrayed animals as so integrally connected that a change in one part, however slight or subtle, would necessarily require compensatory alteration in every other feature in order to maintain a functioning creature. Since such wholesale restructuring for each change is inconceivable, evolution becomes an impossibility. Cuvier’s argument is impeccable in logic and would, indeed, debar evolution if its premise of absolute integration were valid.

Heterochrony achieves its special importance in studies of development and evolution because it embodies this central enabling theme of modularity and dissociation. Heterochrony is defined as phyletic change in the timing of development, such that features of ancestors shift to earlier or later stages in the ontogeny of descendants. This definition is simple enough, but gives rise to a host of practical and theoretical difficulties, and to a rash of consequent literature. Consider just two issues. First, a shift in timing relative to what? Newtonian time in days, developmental time in stages? And what is to be done with paleontological material when no absolute times can be ascertained? Can a surrogate like body size then be used? I tried, with limited success, to develop a ‘clock model’ for resolving these issues (ref. 3, pp. 246-262), but the later formalization of Alberch et al.\(^{(4)}\) is preferable and has generally been accepted as an ‘industry standard.’

Second, a subject can easily be destroyed by attempting to encompass too much. In one sense, and almost by necessary logic, all change must involve timing. If heterochrony involves any change describable by speeds of reactions, then we might as well retire the concept as a synonym of evolution. Heterochrony is a principle of historical legacy and its later, creative consequences — evolution by relative temporal shift of features already present in ancestors, as opposed to introductions of novelties. (I am well aware that apparent novelty, in morphological or functional aspects, may be constructed by altering the rates of ancestral developmental sequences — a fact that demands further complexity in definition. See Alberch\(^{(5)}\) for an excellent discussion and resolution of this issue.) In any event, heterochrony, which once languished in the deepest doghouse of neglected concepts, now ranks among the most popular of evolutionary topics (see, for instance, recent books by McKinney\(^{(6)}\) and McKinney and McNamara\(^{(7)}\) and holds greatest promise as a unifier of the cardinal subjects of ontogeny and phylogeny.

A Short History: Haeckel’s Legacy and Darwinism’s Neglect

The study of development should be the unifying point for integrating reductionist and mechanical studies of genes and cells with historical and narrative accounts of life’s phylogeny, in short, the focus for a truly encompassing biology. Aristotle granted embryology this central role and Darwin’s grandfather Erasmus developed an ontogenetic theory of phylogeny (as were most evolutionary accounts in the progressivist climate of the Enlightenment), and even expressed it in heroic couplets:

See, without parents, by spontaneous birth
Rise the first specks of animated earth...

In Charles Darwin’s age, of course, Haeckel’s biogenetic law, or theory of recapitulation, provided the canonical account of relationship between ontogeny and phylogeny. Expressed in heterochronic terms, Haeckel’s principle required a virtually universal acceleration, or speeding up of development, through evolutionary sequences. In this way, adult characters of
ancestors could become juvenile features of descendants and, ultimately, ontogeny might be read as an epitome of phylogeny: the earlier the stage of development, the longer ago it served as an ancestral adult form.

Haeckel’s theory had a profound influence across Western culture (see chapter 5 in Gould(3)), probably rivalling that of natural selection itself. Recapitulation directed primary school curricula of the late 19th century (since young children were like ‘primitive’ adults, and the legends of these ancient times would therefore resonate with their juvenile souls); it buttressed racism and its colonialist extensions (since ‘lower’ people were like juveniles of ‘higher’ races and needed the same ‘protection’, read domination, as children); and it provided a basis for Freud’s psychological theories (the Oedipus complex repeats, in juvenile males, an actual event of parricide once inflicted by adult sons upon a ruling father — see his books Totem and Taboo, and Moses and Monotheism).

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1. Temper of the times. Late 19th century biology, especially in Germany (then the center of advanced research), favored a rigorously mechanistic and experimental approach embodied in Roux’s Entwicklungsmechanik for studies of development. Roux’s school viewed the inferential reconstruction of family trees from evidence of ontogeny as, at best, of limited value and merely descriptive in nature and, at worst, as fatuous. Roux himself wrote (ref. 8, p. 253): ‘To be sure, we agree with Haeckel’s dictum ... but the biogenetic law merely designates the fact of repetition ... It teaches us nothing about the operating causes and their intensities. The experimental study of developmental mechanics can bring us this knowledge.’ Less diplomatically, the great American disciple E. B. Wilson spoke for modernism from the newly-founded Marine Biological Laboratory at Woods Hole (ref. 9, pp. 103-104): ‘The search after suggestive working hypotheses in embryological morphology has too often led to a wild speculation unworthy of the name of science; and it would be small wonder if the modern student, especially after a training in the methods of more exact sciences, should regard the whole phylogenetic aspect of morphology as a kind of speculative pedantry unworthy of serious attention.’

2. Logic or argument. Recapitulation’s need for universal acceleration found its easiest justification under Lamarckian models of inheritance because new features acquired in adult life are added to the linear sequence of inherited ontogeny, thereby pushing older
changing local environments. Internal genetic factors for development supply the copious, small-scale, fundamentally random variation that acts only as raw material in Darwin’s system. The direction and scope of change are externally determined by natural selection based on selective pressures of surrounding environments.

Why would anyone grant much attention to development in such a system? Development produces variation, but variation itself plays no directing role in its curiously formless status as an isotropic sphere around a modal morphology. In effect, variation may be taken simply as a ‘given’, as a ‘primitive term’ in the argument. (Darwin himself had no other choice, given the ignorance of his age about causes of variation and modes of inheritance.) If variation is always present, and usually unconstraining, why worry unduly about its sources or consequences, so long as one can be confident about its availability. Moreover, Darwinism also downplays the essential internalist theme of small change amplified through development to large effect on adult phenotypes – for strict Darwinsians have always favored accumulative models of microevolutionary extrapolation for major changes, that is, step by step, upward from the world of insensible increments where development becomes largely irrelevant.

The Modern Synthesis, Darwinism’s triumph, was integrative in two senses: first, in bringing Darwinism and Mendelism together; second, in gathering the classical subjects of biology under its umbrella, one by one - Mayr for systematics, Simpson for paleontology, Stebbins for botany, White for cytology, etc. However, embryology and development stayed outside the penumbra. De Beer’s short book *Embryos and Ancestors* (1940)(10), was enjoyed but unexploited while Goldschmidt (1940)(11), who touted the classical internalist themes of constraint and large-scale change, was reviled. Waddington, the embryologist (and ex-paleontologist) who moved most easily in synthetic circles, would blurt out in frustration that his colleagues devised elegant models of allelic change in populations, or studied the most minute shifts of microevolutionary phenotypes, while he wanted to know how evolution made ‘lions and tigers and things.’ Development stood very low on the agenda, if not beyond the pale, of the synthetic theory.

**The New Potential Union of Evolution and Development, and the Centrality of Heterochrony**

Nothing in my entire career has brought me more pleasure than watching (largely passively, after providing a little push by publishing *Ontogeny and Phylogeny* in 1977) the reintegration of evolution and development, from some cautious forays on heterochronic themes to a virtual cascade today as we finally begin to unlock the genetic basis of development. I see two major reasons for this rerouting in parallel of central themes that had diverged for bad reasons.

1. **Elimination of theoretical barriers.** Strict Darwinism, as argued above, contains little room for the internalist themes best illustrated by development: constraints and substantial changes. While strict Darwinism prevailed, development would remain in limbo. However, the hegemony of strict Darwinism has been broken in the past twenty years. This has occurred in a fruitful way that leaves the Darwinian mechanism intact as a centerpiece, while expanding the realm of evolutionary forces and levels to include much else that is centrally concerned with development. The reasons for this expansion are many and complex, and far beyond the scope of this article. However, they include: (i) Expansion of levels above and below Darwinism’s nearly exclusive focus on individual bodies and their struggle for reproductive success – from alleles or nucleotides as the focal level in Kimura’s(12) theory of neutralism, to species in the theory of punctuated equilibrium(13), to clades in theories of mass extinction(14); (ii) Expansion of causes of change to include chance at all levels (allelic neutrality to mass extinction) and developmental constraints as positive channels of preferred change, not merely as negative forces, preventing advantageous alteration.

Much of this ferment can be captured in the beautifully apt metaphor first proposed by Darwin’s brilliant cousin Francis Galton(15) in 1869, and widely invoked by evolutionists (including Bateson and de Vries) before development slipped from popularity. Galton argued that we should view organisms as polyhedral solids. They may not budge unless pushed by the external force of natural selection but, when shoved, they can only move in limited directions specified by internal features of geometry (built, of course, by development). This internal architecture embodies both great development themes: constraint (the polyhedron can only move from one facet to another, and longer pathways of change are internally specified by the forms and interrelations of facets), and substantial alteration (movement must occur by a flip from one stable facet to another). By contrast, in the world of strict Darwinism, organisms are spheres and they move wherever the pool cue of natural selection and the table of environment specify - without any ‘pushing back’ from an internal geometry constructed developmentally.

So profound is this shift of concern that ‘developmental constraint’ has become one of the hottest topics in evolution(16-18), so much so that it threatens to become a ‘buzzword’, too loosely defined and too encompassing. Heterochrony has pride of place among developmental themes in evolution primarily because it represents the most fruitful ontogenetic approach to both major internalist themes of constraint and structurally-aided substantial change. Of all constraints, standard sequences of ontogenetic change are the most immediate and powerful on the obvious principle that
nature works more easily by rearranging what it has than by constructing novelty. Each organism has a great panoply of evolutionary change available within its own growth because so many features alter allometrically through growth, often producing substantial modifications of ontogeny. Given the principle of modularity (see introductory section), these sequences can be dissociated and the relative timings altered. Heterochrony is defined as temporal alteration plus dissociation and it is therefore the chief focus for using current pathways (constraints) in evolutionary change.

Similarly, heterochrony has long supplied the primary macroevolutionary theme for ontogenetic concepts, namely the proposal that small genetic changes, acting early in development, can cascade to large phenotypic effects, providing thereby one of the few legitimate Darwinian rationales for rapid, large-scale change. Such potential pathways are almost always heterochronous, as in the putative origin of higher taxa by progenesis (or the early maturation of larvae with chrony but you (developmental biologists who read this essay) experts—this growing tractability formed my reason for pontificate within an issue filled with articles by real experts—which produced its surface architecture (not to mention its deep structure). All I could do was write a slim final chapter with a few brave words (superficial, however well intentioned) on the putative difference between structural and regulatory genes. I even began the book with a line of apology (1977, p. 1): ‘I am aware that I treat a subject currently unpopular.’

All this has changed dramatically, thanks to your work. Our understanding is still in early infancy, but we now have the tools (from rapid and routine genetic sequencing to labelling and tracing of gene products in ontogeny) to unlock the genetics of development. From an immediately heterochronic perspective, specific genes that regulate rates of development have been identified and characterized in Caenorhabditis elegans (where they have been called ‘heterochronic genes’) and other creatures.

More generally, we are beginning to glimpse the overall development of some complex creatures as a hierarchical series of increasing specificity: from, in Drosophila for example, basic gradient makers (like bicoid) to segmentation genes (like fushi tarazu) to differentiators of particular segments (the homeotics). And the developing explanation of homoeotic function, with discontinuous phenotypic effects, arising along a gradient of concentration, produced by genes arranged in the same order, is among the most elegant stories in all of biology.

Moreover, the clear genetic homology (using the word in its true evolutionary sense of similarity by common descent) between the Drosophila HOM complex and the fourfold-repeated HOX sequences of mice and other vertebrates shows that these disparate phyla still carry complex legacies of common ancestry. (And revives biology's oldest dream of unification, Geoffroy's early 19th century claim for a common architecture to all animal life, as Goethe had advanced a similar theory for plants, based on a leaf archetype.)

The issue of morphological homology is still open for homologous genes may commandeer different phenotypic apparatuses, and the final morphological products need not be homologues. For example, somites and metameres are too structurally and developmentally different to qualify, and this has led to the traditional denial of homology between the phyla. But some remarkable similarities have recently been found between arthropod metameres and a second system of vertebrate segmentation centered on rhombomeres of the developing mid and hindbrain, branchial arches and some cranial nerves. Hunt et al. have just published the intriguing discovery that paralogues in the four vertebrate HOX complexes show identical expression patterns in the rhombomeres, cranial ganglia and branchial arches, but do not work in such a coordinated way in the trunk somites. (As a pure speculation, may this not indicate a phylogenetically primitive status for the rhombomeric system, with the somitic system sur-added, as the HOX duplications continue to build rhombomeres on the old pattern, while working differently with the unique and later somites?) If a paleontological word might be in order, early agnathans (and some pre-vertebrate chordates) have very prominent branchial baskets, presumably a filtration device by original function, with a smaller somitic system, as if a minor trunk and tail were added to a massive frontal device. Rhombomeres are now transient in vertebrates (as branchial arches in tetrapods), but current
prominence is no mark of phyletic precedence. (The frontal segmentation is phyletically confused by the formation of skeletal structures in the branchial region from neural crest, a later and clearly novel vertebrate feature, apparently not influenced by HOX genes. Developmental biologists who wish to explore the possible morphological homology of arthropod metameres and vertebral frontal segmentation might try to subtract the neural crest derivatives and focus on development of what may remain from the old branchial basket segmentation.)

In any case, this developing (and fast-breaking) story strongly increases the probable significance of constraint and heterochrony in evolution and greatly diminishes the fading, strict Darwinian idea that evolution may be traced as insensibly transitional adaptation to external environments, without close attention to how internal architecture channels and structures the potential pathways of substantial change. If groups so disparate as arthropods and vertebrates bear substantial homology in basic morphological design, then constraints on pathways are legion and life’s commonality will be resolved more by the study of development than by adaptation.

A Mozartian Epilogue: Cosi Fan Tutte

To end where I began (as I write this article in the very month of Mozart’s bicentennial), consider his opera _Cosi Fan Tutte_ as an epitome of the history of relationships between developmental and evolutionary biology. The two couples of the opera are initially joined in tirades of romantic pledges about eternal devotion, but in total youthful naïveté (and therefore with no firm foundation) - just as ontogeny and phylogeny were so strongly fused under the false banner of Haeckel’s biogenetic law. The couples are then separated in growing hostility and claims of betrayal - only to reunite at the end when they accept each other’s errors, foibles and failings, thereby forging a true bond based on practical knowledge rather than inconstant emotion (a favorite theme of the Age of Reason, quite explicitly extolled by Mozart against romanticism). So, too, for development and evolution, two fields that needed to separate when the false focus of previous union became clear, but that now can reunite, both older and wiser, with the discovery of a true and lasting basis for synthesis. It is an old story - _Cosi Fan Tutte_ (all women are like that – men too, as the non-sexist opera makes quite clear). Professions, in many ways, are like people. And when they finally join for the right reason, look for the cascade of fruitful progeny.

References


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