Evo-devo has led to dramatic advances in our understanding of how the processes of development can contribute to explaining patterns of evolutionary diversification that underlie the endless forms of animal life on the Earth. This is increasingly the case not only for the origins of evolutionary novelties that permit new functions and open up new adaptive zones, but also for the processes of evolutionary tinkering that occur within the subsequent radiations of related species. Evo-devo has time and again yielded spectacular examples of Darwin’s notions of common ancestry and of descent with modification. It has also shown that the evolution of endless forms is more about the evolution of the regulatory machinery of ancient genes than the origin and elaboration of new genes. Evolvability, especially with respect to the capacity of a developmental system to evolve and to generate the variation in form for natural selection to screen, has become a pivotal focus of evo-devo. As a consequence, a balancing of the concept of endless forms in morphospace with a greater awareness of the potential for developmental constraints and bias is becoming more general. The prospect of parallel horizons opening up for the evolution of behaviour is exciting; in particular, does Sean Carroll’s phrase referring to old genes learning new tricks in the evolution of endless forms apply equally as well to patterns of diversity and disparity in behavioural trait-space?

Keywords: evo-devo; evolvability; developmental bias; morphology; endless forms

1. SOME ACHIEVEMENTS OF EVO-DEVO

With respect to Darwin’s endless forms, modern evolutionary developmental biology, or evo-devo, has demonstrated beyond any doubt the truth of his principles of common ancestry and of descent with modification. A half-century ago, few would have considered it likely that diversification of a single ancient and highly conserved tool kit of signalling genetic pathways had provided the basis for the evolution of morphology throughout the animal kingdom, or that the set of developmental genes in a fly would have so much in common with that of our own species. Research is revealing how, to employ Sean Carroll’s now famous phraseology, the evolution of form is largely about ‘teaching old genes new tricks’. Carroll [2] has emphasized how the multiple functions and contexts of these genes in development (both spatially and temporally) constrains evolutionary change to the regulatory machinery of the genes rather than to the proteins themselves (the demonstration by Halder et al. [3] of the ability of the mouse Pax-6 protein to induce ommatidium formation in Drosophila, just like the Drosophila Pax-6 (eyeless) protein itself, retains its power to impress). Many of these developmental genes code for transcription factors that regulate the activity of other genes, often via interactions with other transcription factors and proteins. Typically they regulate the expression of numerous target genes in complex genetic regulatory networks and, thus, lead to the activity of cascades of genes in cell differentiation and development. There are of course demonstrations of protein change in morphological evolution. Some, but not all [4,5], of such examples involve proteins with more specialized roles in development such as in pigmentation or in the ear (e.g. [6,7]). While clearly there are also important examples of taxonomically restricted genes (e.g. [8]), some of which contribute to development, the conserved tool kit of signalling pathways is involved in so much of what happens in morphogenesis throughout the animal kingdom.

Perhaps, in hindsight, there is little reason to find such general properties of the diversification of form especially surprising or unexpected. Evolutionary biologists are used to the notion that the process of evolution is highly opportunistic; if a particular feature or property is available, evolution will exploit its potential and run with it, somewhere and somehow. Micro-RNAs and the growing evidence of their important role in gene regulation provide a good example of this. It seems then, rather logical that tinkering with, and the reuse of, existing systems will tend to happen much more often than inventing and designing new systems, de novo, for the evolution of form.
extensive pleiotropy of such existing genetic systems in their developmental context will then lead to bias in the mechanisms by which evolutionary change tends to occur. Although evolution will happen in different ways, evo-devo has led to the recognition that certain types of genetic change predominate, and adaptive hotspots are likely to occur in the genome with respect to the diversification of form [9]. The details of the types of change in genetic regulation that have been associated with the origins of evolutionary novelties involving morphology may, however, tend to involve different ways of modifying the networks from those that dominate the subsequent tinkering process in character transformation [9]. It is in any case comparatively easy to begin to make generalizations now we know much about the principles of how genes coordinate the development of complex morphologies. Such general principles for the evolution and genetics of diversification of behavioural traits are yet to progress as far but will surely be an exciting field in years to come, and one likely to yield different trends from those for form.

2. EVOLUTION OF FORM AND ON TO THE EVOLUTION OF BEHAVIOUR

Development is central to the evolution of form because it translates genotypes into morphologies. Mutations and genetic variation are the raw material for evolution, but the developmental processes of morphogenesis build the variation in form that is screened by natural selection to yield organisms adapted to their environment. Animal groups with spectacular differences in body plan, not to mention all the products of evolutionary tinkering with such designs, have used the same basic machinery to yield disparity in form. The field of evo-devo is unravelling the puzzle of how the ancient tool kit has been employed via the evolution of complex regulatory machinery to build such an astonishing variety of animals with such disparate morphologies. It is this architecture of development which when coupled with the processes of natural selection and evolution accounts for the awe-inspiring range of morphologies exhibited by biodiversity on the Earth. Biology is indeed edging ever closer to a detailed understanding of how the processes of natural selection and evolution contribute to the evolution of form. The field has examined how changes in developmental pathways account for the evolution of disparity in form across distantly related taxa with highly divergent body plans and, increasingly, also among closely related species. This work is exploring the extent to which the same sorts of pathways and changes are involved at different phylogenetic levels. The connections between patterns at the macroevolutionary level and microevolutionary processes observed within populations on an experimental time scale remain essentially unmade [12]. However, advances that will help to resolve these connections are being made through work on subtle differences in phenotype such as occur for bristle patterns or wing-spotting in dipteran flies [13–16], and the studies of evolutionary novelties involved in major, novel structures such as limbs, segments, eyes and fins [17–19]. Among the systems currently under study with exciting potential for integrating the micro- and macro-levels of evolution in form are vertebrate teeth [20,21], and the pelvic fins and armour of stickleback fish [22].

The results of research in evo-devo are also beginning to tackle whether the way in which development works could influence the sets of morphologies that evolve within morphospace. Dramatic examples of parallel evolution in form, such as in the species flocks of haplochromine cichlid fishes of the African Rift Valley lakes [21,23], could be influenced by biases in the capacity of the relevant developmental pathways to generate variation in certain axes of
morphospace relative to others. These chilids appear to show a small number of distinct trophic morphologies (not to mention behaviours and life histories), which may reflect more or less discrete clusters of species, each with a different way of making a living. Developmental biases could also have played a role in the evolution of the different morphologies of teeth along the jaw of a mammal [20,21], or the appendages of different segments along the body of a crustacean [24,25]. Again, the way in which development works and the evolvability of teeth or appendages could help to explain the different functional morphologies that have—or indeed have not—evolved from some ancestral jaw or body axis carrying repeated copies, each of similar form. The evolution of individuality in the form of the serially repeated eyespots along the margin of a butterfly wing involves comparable issues [26–28]. Similar types of questions can also be posed with respect to the evolution of disparity in behaviour.

Thirty years or so ago, development in an evolutionary context was essentially a black box positioned between genotype and form; development mapped form onto genotype but was largely unknown, at least from the genetical perspective. Thanks to the extraordinary advances of developmental and molecular genetics, the contents of the black box have become visible. What have we learnt and how is this likely to transfer to other components of the phenotype, especially behaviour? The concepts that have flowed from opening up this box for morphogenesis may ultimately help with the challenge of understanding the evolution of the whole functional phenotype where physiology and other processes must play more prominent and integrative roles.

Evolution of form is highly opportunistic. The machinery of tool kit genes, master control genes and signalling pathways is used time and again both within ontogeny from the zygote to the adult organism, and in very different structures, tissues and organs. It is the evolution and reorganization of the developmental gene regulatory networks for this machinery that appears to underlie much of the evolution of morphology [2,19,29]. To almost any student of biology from the 1970s or earlier, the great discoveries of developmental biology over recent decades are truly inspiring revelations. The next quarter of a century will clearly reveal more of how the genotype to phenotype map works for the whole functional phenotype, and will demonstrate the extent to which the evolution of form is special with its own largely private mechanisms and machinery. How do the principles being observed for the evo-devo of form apply to behaviours and life histories, and do the patterns of change in the genes which regulate such traits parallel those for form?

Development and evolution are clearly deeply intertwined, and as Hall [30] has emphasized, it makes no sense to study them in isolation. Any evolutionary change in form must involve some modification in development. Also, any absence of change in form over a very long period of time (morphological stasis) begs the question of why in terms of development some pattern of dynamic evolution has not occurred [12]. Developmental and behavioural plasticity in response to environmental conditions are additional processes likely to play a crucial role in shaping the evolution of form, both in terms of the phenomena of phylogenetic constraints or inertia [31] and of facilitating patterns of diversification, perhaps involving genetic accommodation [32,33]. The study of such processes will contribute to a blossoming of the extension of evo-devo becoming known as eco-evo-devo [34], in which both plasticity and the environment are a focus of attention.

4. EVO-DEVO AS A DISCIPLINE

A variety of concepts have become important focal points for discussion during the era of modern evo-devo in an attempt to integrate the two fields, and tie down the goals of evo-devo. Modularity, developmental integration, developmental constraints, emergence and evolvability together with many related ideas have all been targets for much discussion [11]. Such discussions have not always been based on rich sets of empirical data, but this is changing as more experimental and analytical work is performed using an increasing range of systems.

Comparative embryology has enjoyed a long and rich history, and is clearly ancestral to modern evo-devo in terms of many of the research problems (e.g. [35]). Developmental constraints and the role of heterochrony were a core problem of comparative evolutionary embryology. The association between evolution in form and the timing of modification of development in ontogeny remains unclear, especially with respect to evolutionary novelties. Associations of this type will also prove fascinating to unravel for behavioural traits.

The success of exploring the molecular genetics of embryogenesis in combination with the broad field of developmental genetics is at the core of evo-devo. Developmental biologists have revealed how the processes of embryogenesis and morphogenesis are regulated by genes and signalling pathways. Much of the early effort in integrating evolution and development examined how differences in body plan are organized and specified [17,36,37]. Major body features such as segments, limbs and eyes were compared in a small number of model organisms with highly disparate morphologies. These studies discovered differences, as well as many remarkable similarities, in the developmental mechanisms employed by different phyla. They demonstrated that the signalling pathways used by animal cells in all phyla are ancient and highly conserved. The complete pathways are homologous across the metazoan from arthropods to vertebrates; they are also surprisingly few in number. The association of the Pax-6 gene with the development of the eyes of flatworms, arthropods and vertebrates is a particularly dramatic example. An important focus in this work has been to examine how modifications of developmental processes can lead to the production of the new morphological features of evolutionary novelties [18,38,39]. Similarly, the sorts of modifications that are involved when organs are lost are being
increasingly revealed, for example, in research on blind cave fish [40–42].

The field of evo-devo is also becoming increasingly concerned with the differences in form among closely related species [43]. Waddington [44] considered how development could influence the expression of phenotypic variation. Wim Scharloo and other researchers galvanized by the Edinburgh school of developmental and quantitative genetics were forerunners of current work on the developmental basis of more subtle differences in morphology. Examples in insects include the cuticular bristle patterns of flies [13,15], the wing spots of flies [14,16], the horns in dung beetles [45,46] and the eyespots along the margins of a butterfly wing [26,27]. An early gathering of researchers [47] from both the developmental and the evolutionary fields established an important milestone in defining a developmental constraint as a bias on the production of various phenotypes caused by the structure, character, composition or dynamics of the developmental system. The field remains a long way from any complete description and analysis of such bias and its effects on the occupancy of morphospace [48], but progress is being made [49]. Hopefully, future work will unravel more effectively the genetical from the developmental properties.

5. EVOLVABILITY AS A FOCUS FOR THE EVOLUTION OF FORM

Evo-devo seeks to answer a variety of different questions but many of these have their roots in the concept of evolvability. Hendrikse et al. [50] have recently argued that the proper focus for evo-devo is evolvability [51]. Such a pivotal focus is indeed logical and certainly encapsulates the reason why so many evolutionary biologists have become enthused by the field. Does knowledge of how forms are built help evolutionary biologists to account for the directions and rates of evolution in morphospace? Some even consider that the results of this endeavour may lead to a reassessment of the modern synthesis [2,11,52].

Knowledge about the properties of evolvability must be at the heart of explanations of patterns in evolution, especially perhaps with respect to how radiations of species explore morphospace [28]. From a developmental perspective, evolvability is perhaps best defined as the capacity of a developmental system to evolve, which is primarily a function of its ability to generate variation in form. The efficacy of natural selection depends on the availability of appropriate variation in the phenotype. This is in turn not only dependent on genetic variation, but how this is translated to yield variation in the phenotype; that is, in the case of form, on development and morphogenesis. In essence, if evolvability with respect to the ability of development to generate the fuel for natural selection to screen for functionally effective phenotypes differs among potential directions of change, the paths that evolution follows can be expected to be biased. The extent to which natural selection is all-powerful in different organisms remains unclear whether one is considering morphological, behavioural or life-history traits (e.g. [12,49,53]). Perhaps.

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ecospace-limiting constraints do tend to be more influential than any developmental constraints for the evolution of form (e.g. [54]), and given time biases arising through the properties of evolvability tend to be of comparatively minor consequence. However, time to adapt is not always available for a population confronted by an environmental challenge, especially in today’s rapidly changing world. More research is clearly needed that seeks to explore in an integrative manner the intrinsic effects resulting from the generation of variation in the functional phenotype and the extrinsic effects resulting from the process of sieving that variation by natural selection.

Similar considerations can also be applied to the origin of evolutionary novelties [55]: are these rare because of developmental constraints or is their appearance primarily driven by natural selection? Eberhard [56] argues that his surveys of male secondary sexual traits in sepsid flies support a retarding effect of developmental constraints, although his conclusion has been questioned [55]. Again, evo-devo is making advances here in our knowledge of the development of such structures [57,58], and it is to be hoped that this work will help to resolve the role of developmental processes in the evolution of the observed patterns in morphospace. This case study also illustrates again the intricate interactions between form and behaviour since these novel structures in male sepsid flies can only be functional and influence mating success when coupled with the appropriate behaviours and signals [56,59].

The origin of evolutionary novelties is one aspect of evolvability; another is the role of standing genetic variation and mutational input in generating developmental flexibility. However evolvability is defined—and this is to some degree dependent on the perspective of the researcher—it is crucial to discover the extent to which both genetics and development influences the generation of variation in the phenotype. Evo-devo, at least for the forms of organisms, must in its broadest sense be capable of helping to reveal the importance of differences in evolvability for the observed patterns of occupancy in morphospace, as well as for making predictions about the likely effects of environmental change. Again, it is simplistic, and indeed potentially misleading, to consider the evolution of form without taking into account its interactions with behaviour in the arena of selection. The evolvability of butterfly eyespot patterns in different directions of morphospace can be explored experimentally by artificial selection and the responses analysed in terms of both genetic and developmental mechanisms [27], but ultimately how such phenotypes will evolve will depend on their interactions with behaviour and ecology [28]. An integration of experimental work on key traits using model species with a more comparative phylogenetic approach across species in eco- and trait-space is needed to progress further.

A system can be considered to be evolvable if it can be modified through genetic change in a way that could potentially enhance survival and reproduction. Some traits may be more evolvable than others, and evolvability may depend on the direction of change.
in phenotype. The relationship between evolvability and different forms of robustness, for example mutational robustness, is controversial (but see [60]). Thus, mutational robustness implies that the system produces little phenotypic variation in response to genetic variation, which would be expected to hamper the response to natural selection. On the other hand, robustness is expected to facilitate the accumulation of cryptic genetic variation which could foster such responses under certain conditions of environmental perturbation and some form of failure in the mechanisms of robustness. In particular, this could be an important process when considering access to new adaptive peaks or a region of high fitness surrounded by a valley of low fitness. From a developmental perspective, it will be exciting to be able to differentiate more clearly between these types of effects. Detailed experimental work to untangle such processes is progressing with proteins (e.g. [61]), RNA viruses (e.g. [62]) and bacteria (e.g. [63]), but has hardly begun for the development of morphological traits in higher organisms. Perhaps in the future, it will also be possible to extend considerations of how the evolution of behaviour depends on evolvability and robustness in development.

Developmental bias [47] and genetical channelling [64] can in theory arise from patterns of shared developmental pathways or genetic covariance among traits. Distinguishing between such terms as the most appropriate label for a difference in patterns of response to natural selection on morphological traits will always be challenging. Because the processes of establishment of behavioural traits will involve a broader set of underlying mechanisms, one which will include development, this is likely to be even more challenging for such traits. However, in principle, sufficient information at different levels of the process of translation from genetic variation to expression of the trait itself should enable a proper distinction to be made. In any case, such distinctions may not be very informative except to illustrate that any one-sided or reductionist approach, one which, for example, considers only genetic variation, is unlikely to capture the underlying processes sufficiently to be able to predict fully responses to natural selection and environmental change.

6. TRENDS IN EVO-DEVO

Case studies that use molecular developmental genetics to uncover the types of changes in genetic machinery that have been involved in the evolution of form are expanding rapidly both for deep and shallow phylogenetic nodes. Although the field remains somewhat controversial with respect to the overall contribution of cis-regulatory change [65, 66], it is clear that modification in the regulatory machinery of developmental genes plays a crucial role in the evolution of form. This process also clearly helps to explain how the limited sets of developmental genes and genetic signalling pathways can underlie morphogenesis in higher organisms of so many different types of cells, tissues and structures, and at different stages of ontogenesis. How exactly this machinery has been recruited and co-opted at the origin of some novel structure, and then elaborated upon in subsequent adaptive radiations in morphospace facilitated by the structure remains an exciting challenge for the future [19]. The roles of the processes of developmental plasticity and epigenetics, and of so-called cryptic variation, are also fields that are clearly important to understand more fully. It will also be fascinating to determine how readily generalizations for the evolution of form can be extended to behavioural traits, and to the evolution of interactions between form, physiology and behaviour that underlie any coordinated, functional phenotype.

One of the clearest trends in evo-devo has been the increasing contribution made by research on a range of emerging model organisms [67, 68]. Functional tests of candidate genes and genetic variants, especially using RNAi, are also becoming widely available for these organisms. These efforts have been coupled with an ever-widening variety of types of morphologies under investigation, and with an extending interest from the opening up of developmental genetics through to studies of function, performance and natural selection on the same traits. This reflects one of the achievements of the field in expanding its horizons beyond the deepest nodes in phylogenetic evolution towards understanding the contribution of development at all levels of biological organization, throughout ontogeny, and from evolutionary novelties to the effects of evolutionary tinkering with form. The era of modern evo-devo was ushered in by developmental biologists concerned with probing the differences in developmental processes underlying the major differences in body plan among the small number of model organisms, but this has been increasingly transformed to yield a much broader perspective. The same healthy trends can be predicted for the research community working on the development of behaviour.

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REFERENCES


