



## How developmental is evolutionary developmental biology?<sup>1</sup>

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**Abstract.** Evolutionary developmental biology (evo-devo) offers both an account of developmental processes and also new integrative frameworks for analyzing interactions between development and evolution. Biologists and philosophers are keen on evo-devo in part because it appears to offer a comfort zone between, on the one hand, what some take to be the relative inability of mainstream evolutionary biology to integrate a developmental perspective; and, on the other hand, what some take to be more intractable syntheses of development and evolution. In this article, I outline core concerns of evo-devo, distinguish theoretical and practical variants, and counter Sterelny's recent argument that evo-devo's attention to development, while important, offers no significant challenge to evolutionary theory as we know it.

### Introduction

Embryology, so impressive in its experimental heyday, suffered as a science while genetics established a monopoly position in biology in the first half of the twentieth century. The geneticists' successes were due largely to their tremendously productive, simple models, whereas experimental embryology was anything but simple. Classical geneticists black boxed the knotty mess of development, in that their study of heredity encompassed only the transmission of genes and not the development and reproduction of organisms (Gilbert (1978), Allen (1986), p. 120; Sapp (1987)) – even though classical genetics did contain a theory of development grounded in simple views about gene expression (Sarkar 1999). Prior to about 1910, T.H. Morgan, trained as an embryologist, was concerned about this lacuna in genetics, namely that “between the characters, that furnish the data for the theory, and the [at that point, only] postulated genes, to which the characters are referred, lies the whole field of embryonic development” (Morgan (1926), p. 26). By 1919, though, he believed that “one could account for ‘the organism as a whole’ in terms of ‘the collective interaction of genes’” (Morgan (1919), p. 241). A few years later, in 1926, Morgan concluded that “the application of genetics was a most promising method of attack on the problems of development” (Sapp (1987), p. 50; Morgan

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<sup>1</sup> This title is adapted from Laubichler and Wagner (2001)

(1926), pp. 491–496), thereby helping to shape the study of embryology virtually ever since.

In the 1940s, embryology was left out of biology's Modern Synthesis of genetics, zoology, and botany, *inter alia*, under the umbrella of population genetics. Within the Synthesis, evolution was defined as an "epiphenomenon of the genetics of populations" (Gilbert et al. (1996), p. 358). Population genetics is insensitive to anything like actual developing organisms in their present and historical complexity, for in a population genetic conception of evolution, reliable development is simply presupposed. (This is the straightforward result of a focus on populations *in lieu* of individuals.)

But development has not been altogether ignored since the 1940s – far from it. "Just as evolution became redefined as the study of changes in gene *frequency*, so embryology became redefined as the science studying changes in gene *expression*" (Gilbert et al. (1996), p. 360). So construed, embryology (now developmental biology) has demanded considerable attention from biologists over the past half-century. Ever since the Modern Synthesis, both evolution and development have been studied (usually independently) primarily in terms of genetics; hence, for instance, a population genetics relatively ignorant of development, and a developmental genetics relatively ignorant of evolution.

The reconceptualizations of evolution in terms of population genetics, and of development in terms of gene expression, are well reflected in the history of the philosophy of biology. Philosophers have long been preoccupied with evolutionary theory, and more recently with molecular biology, but far less frequently with development. Though historians of biology have been long intrigued by embryology, philosophers have tended to shy away. From a philosophical vantage point, one reason is that, as against the tradition in genetics, embryology was usually seen to be swaddled in a blanket woven of vitalistic and mystical strands: embryology seemed committed to some profoundly anti-materialist doctrines, largely out of vogue in both biology and philosophy since the early part of the twentieth century (see, e.g., Gilbert and Sarkar (2000) on embryology and organicism). Yet times have changed. Mainly as a result of recent work in developmental and molecular biology, some of the reductionistic biases of genetics have paradoxically come to be seen as constricting future research and precluding genuine understanding of both development and evolution (Keller 1999, 2000). Advances in biology generally have permitted us to open the black box of development, and to move beyond simplistic models of gene expression. These scientific investigations have opened logical (and speculative) space for philosophical investigations of the nature of development and its relation to evolution.

Even with development in a black box, genes alone do not explain development; nor do genes alone explain evolution (see, e.g., Laubichler and Wagner (2001)). As we have come to learn these lessons, and also the correlative lesson that the interpenetration of development and evolution cannot be accounted for in strictly genetic terms, a new synthetic framework has emerged within biology. Broader than prior genetic paradigms, though building on them in important ways, evolutionary developmental biology (commonly known by the sobriquet "evo-devo") is generat-

ing considerable scientific and philosophical excitement. The time has arrived to limn the shape and probe the scope of evo-devo.

### **Two caveats about language**

The literature on developmental biology's encounter with evolution tends to fall victim to a touch of semantic slippage, between the 'reconciliation' of developmental and evolutionary biology, their 'integration' (or 'reintegration'), the 'accommodation' of one within the other, and their 'synthesis'. In what follows, I will prefer the latter characterization, inasmuch as I will attempt to show, as others have done, that a synergistic third domain emerges where the domains of developmental and evolutionary biology (and much more, besides) meet.

But here there is a second problem with language. This article is about the particular synthesis known as "evolutionary developmental biology" ("evo-devo"). Arthur (1997), Hall (1999, 2000a), for instance, prefer this locution; other biologists, though, such as Wagner (2000), Wagner et al. (2000) prefer "developmental evolution" or "developmental evolutionary biology" ("devo-evo"). One way of parsing the putative distinction is to claim that, in evo-devo, the primary *explanandum* is development, and evolution is part of the *explanans*; while in devo-evo, the primary *explanandum* is evolution, and development is part of the *explanans*. But it is not yet entirely clear whether this approach to distinguishing evo-devo from devo-evo will work, for many biologists (Arthur, Hall, and Wagner among them, I think) take *both* evolution and development as *both explanandum and explanans*. I shall not resolve this issue here (though some resolution may be found in these pages in a special issue to appear in 2003). Suffice it for now to suggest that this complex issue is more than a semantic one, but also that its final resolution is not required for the discussion of evo-devo to follow.

### **Prospects for synthesis**

Kim Sterelny, among others, has begun crucial investigation into the synthesis of evolutionary and developmental biology (and more). In a recent paper (Sterelny 2000), he has surveyed three visions of a new synthesis. In the first of these three scenarios, development is conceived as a mere background condition to evolution, as developmental possibilities are thought to generate, in an unbiased manner, potential variation around actual phenotypes. Though it is intuitively odd to describe the provision of the material conditions for evolution as a "mere background", the "mere-ness" qualifier stems entirely from the idea that developmentally produced variation is putatively *unbiased*. So, in this first vision, the role of development in evolution is to provide undirected phenotypic variation. The second scenario posits a more directive role for development, such that, due to developmental constraints, only particular kinds of variation (and hence only particular evolutionary trajectories) are developmentally possible. Sterelny suggests that in neither case is the

theory or practice of evolutionary biology significantly altered (Sterelny (2000), p. S385).

The third scenario Sterelny considers is more speculative, and would require changes in theory and practice, for on this latter view, appreciating development changes the analytical focus of evolutionary studies. According to Sterelny, evolutionary biology presently unpacks adaptations in what he calls the “variation/selection/variation/selection cycle” (Sterelny (2000), p. S385). But on this third view, the fundamental problem for evolutionary biology is no longer primarily to explain adaptation as such, but rather to explain the very possibility of the evolution of complex adaptations: that is, to explain evolvability (more on this below, in the section “Developing Evolution”).

Sterelny concludes that the plausibility of these three scenarios will be determined on an empirical basis, as biologists learn more about how and how often development biases evolutionary outcomes. But, he insists, in any case, there is no “fundamental conceptual problem for evolutionary biology on any of these three views”. Thus, according to Sterelny, synthesizing developmental and evolutionary biology should be both straightforward and painless (Sterelny (2000), p. S386).

### **A further caveat: Evolutionary biology**

Is Sterelny right? At base, this depends on what one means by “evolutionary biology”. Philosophical debates about development and *evolution* seem often to be rather about development (actually, developmental genetics) and the *Modern Synthesis*. But evolutionary biologists have come a long way since the Synthesis; aside from those few biologists who deem the Modern Synthesis unassailable, and also aside from hard-line Neo-Darwinians (mainly gene selectionists), the views of most contemporary evolutionary biologists have evolved significantly away from the Modern Synthesis (especially with the advent of cladistic analysis, the emergence of comparative genomics and molecular phylogenetics, and so on). *Prima facie*, it appears that synthesizing developmental biology and Neo-Darwinism is a much more difficult prospect than synthesizing developmental biology and evolutionary theory more broadly construed.

At any rate, *defining* what evolutionary theory today actually *is* is no simple task; below, I sketch an account of Neo-Darwinism that is not up to the challenge proffered by attention to development. I presume that it is non-controversial to suggest that evolutionary theory attends at its core to variation, heredity, and differential reproduction (Lewontin 1970; Wimsatt 2001), explanation of evolutionary change by reference to the mechanisms of natural selection and drift, and tracking of evolutionary change by reference to changes in gene frequencies in populations – although some controversy might persist over the exact referents of these concepts or the appropriate scope of their applicability (Sterelny and Griffiths 1999).

### Elucidating Sterelny's position

In making his case, Sterelny mentions a fourth synthetic vision, that of developmental systems theorists (particularly Gray (1992), Griffiths and Gray (1994), Oyama (2000)); he argues that the developmental systems emphasis on the processes of development is in no way integral to understanding evolution. Even were that true in general – and I am not convinced that it is (see Robert, forthcoming) – the conclusion does not follow that studying development and studying evolution fit together as hand in glove.

Let me complicate Sterelny's vision of synthesizing scenarios, beginning by imagining them along a continuum (Figure 1). Although the idea of a one-dimensional continuum is wrongheaded, inasmuch as it collapses the multi-dimensional space of theoretical (and practical) possibility, Sterelny's discussion does seem to imply that he views the various positions as existing along a continuum – that is, as a matter of degree to which focusing on development alters evolutionary theory. Bearing this in mind, imagine that, at the right-hand end of the continuum, we find both Neo-Darwinism and the Modern Synthesis encompassing, roughly, the presumption that development is so reliable, and generative of so much phenotypic variation, that development may be simply assumed in the effort to understand evolution as changes in gene frequencies in a population. In fact, the logical structure of the Modern Synthesis precludes the explanation of the creation of variation, in favour of explaining what happens to variants. Those evolutionary biologists who have incorporated the possibility of developmental constraints would be near but not at the right end of this continuum, as evolutionary theory emerges virtually unchanged from this encounter with developmental biology.<sup>2</sup> At or near the right-hand end, then, are the first two scenarios that Sterelny surveys.

At the other end of the continuum is developmental systems theory (DST), committed to the alternate view that, while development and evolutionary theory may be reconcilable, a new synthesis of development and evolution will not be achieved without significant alterations in core evolutionary foci and concepts (units of selection, units of inheritance, the nature of fitness, and so on). Sterelny, as I have noted above, is too quick (or, at least, arguably so) to dismiss the DST account, and

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<sup>2</sup> It might be objected that an evolutionary theory integrating developmental constraints is much further toward the middle of the continuum than I imply, such that evolutionary theory is transformed in important ways by this encounter. That argument is correct, but only under the assumption that evolutionary biologists concerned with constraints are in fact concerned with (developmental) constraints on form (constraints<sub>F</sub>) and not merely (evolutionary) constraints on adaptation (constraints<sub>A</sub>) (Amundson 1994). Constraints<sub>F</sub> are restrictions on possible types of organic form, whereas constraints<sub>A</sub> are restrictions on adaptation; constraints<sub>F</sub> may result in constraints<sub>A</sub>, but there is no necessary relationship between the two. In other words, constraints<sub>A</sub> are a subclass of constraints<sub>F</sub>. Evolutionary theory's encounter with constraints<sub>F</sub> would surely involve a transformation in evolutionary theory (as the objection predicts); but evolutionary theory's encounter with constraints<sub>A</sub> generates quite minor changes by comparison. My claim in the text is that evolutionary theorists have yet to fully digest constraints<sub>F</sub>.

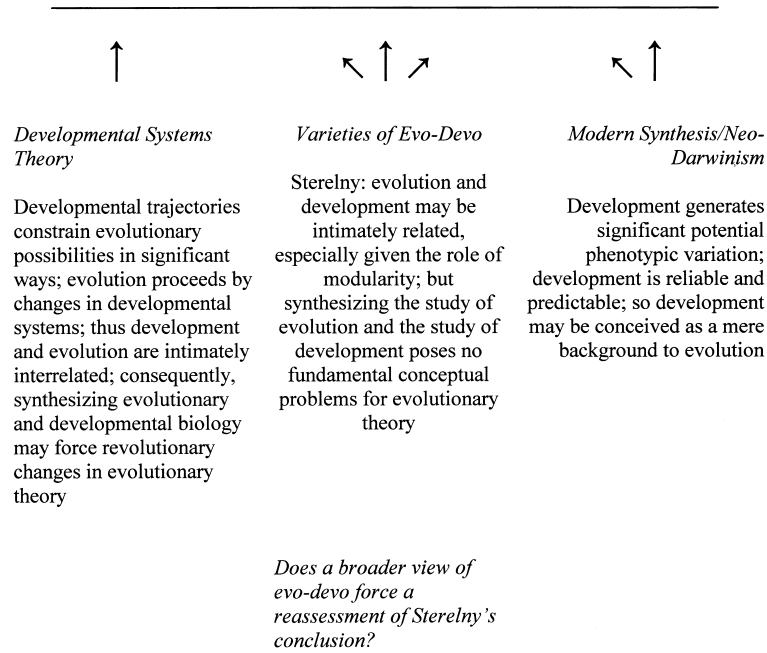


Figure 1. A Continuum of Synthesizing Scenarios. See text for details.

so does not survey it in his (2000) as a real live option (but see Sterelny et al. (1996) for more in-depth coverage of DST; see also Robert et al. (2001)).

Where does Sterelny's third synthesizing scenario fit on this continuum? The third scenario is Sterelny's version of evolutionary developmental biology (evo-devo). On this view, according to Sterelny, while development is indeed important to evolution, and especially to explaining the possibility and the mechanics of evolving complex adaptations, it can be synthesized with evolutionary theory quite easily. Accordingly, this third vision fits somewhere in the middle of the continuum.

My claim is that Sterelny's version of evo-devo represents but a narrow slice of the realm of evolutionary developmental biology. That is, there are other varieties of evo-devo to be found in the middle area along the imagined continuum, not all of which would map well onto Sterelny's account of evo-devo. If any of these could be shown to offer a plausible challenge to, though perhaps not a revolution in, mainstream evolutionary theory, then it follows that Sterelny's conclusion – that evolutionary theory can be synthesized with developmental biology without substantial theoretical fallout – is premature. After exploring evo-devo in the next two sections, I develop just such a challenge. My strategy will be to begin by defending, to a point, the middle position Sterelny entertains, and then to explore just how evo-devo may offer a more significant challenge to evolutionary theory than Sterelny suggests.

## Evolutionary developmental biology

Evolutionary developmental biology compensates for the past half-century's selective forgetfulness (in the biological mainstream) that "development and evolution are neither mutually exclusive, nor under independent control" (Hall (1999), p. xvi). In the nineteenth century (in the work of Haeckel, Gegenbaur, Lankester, and Balfour, for instance), and in the first half of the twentieth century (primarily, though in very different ways, in the work of Garstang, de Beer, Whitman, Waddington, Schmalhausen, and Goldschmidt), connections between evolution and development were established in multifarious productive ways (see, e.g., Gilbert (1994, 2000), Gilbert et al. (1996), Hall (1992, 1999, 2000b)). But these connections were largely lost or forgotten in the twentieth century, and have only recently been rediscovered and reinvested with scientific importance in the field of evolutionary developmental biology (e.g., Bonner (1982), Raff (1996), Arthur (1997), Hall (1999)).

Spanning evolutionary, developmental, molecular, cell, and organismal biology, in addition to genetics, paleontology, morphology, and ecology, evo-devo is a new biological synthesis. Evo-devo has textbooks (e.g., Hall (1999)), journals,<sup>3</sup> and a society<sup>4</sup> helping to establish its professional credentials, while its scientific credentials are beyond reproach. Like any field of biology, evo-devo commands a diverse range of theoretical perspectives and experimental approaches: some evo-devoists focus more heavily on developmental genetics (say, on the roles of homeobox genes in development and evolution [as in Patel (1994)]), some less so (witness Hall (1999) and Gerhart and Kirschner (1997), who focus more closely on cells and their interactions).

Nevertheless, evo-devoists tend to hold to a core of theoretical presuppositions, including: (A) the hierarchical nature of development and evolution; (B) the need to focus on developmental processes – interactions – between genotype and developing phenotype; and (C) the belief that analysing developmental processes and mechanisms, and their evolution, improves our understanding of both development and evolution.<sup>5</sup> Studying development in evolutionary context, and evolution in developmental context, increases the explanatory scope of both sciences. I will focus first mainly on evo-devo's account of development.

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<sup>3</sup> *Evolution and Development* and *Journal of Experimental Zoology (Molecular and Developmental Evolution)* are leading exemplars, though many biology journals (such as *BioEssays* and *Nature*) publish work in evo-devo.

<sup>4</sup> The *Society for Integrative and Comparative Biology* now has an evolutionary developmental biology division.

<sup>5</sup> Core topics of study in evo-devo not explicitly discussed here include: cell determination and differentiation; cell lineages; embryonic inductions; segmentation and compartmentalization; heterochrony; homology and homoplasy; larval evolution (life cycle stages sometimes evolve independently); life history strategies; inferences about the fossil record; and phenotypic plasticity. For an overview with references aplenty, see Hall (1999). Hall and Olson (forthcoming) is an encyclopaedia of keywords and concepts in evo-devo addressing these and other elements of the field.

- (A) – the hierarchical nature of development and evolution – necessitates the study of emergent properties inexplicable from lower (or higher) hierarchical levels; for instance, cells' collective behaviour during morphogenesis cannot be explained (or predicted<sup>6</sup>) by examining the behaviour of individual cells prior to cell division, differentiation, or condensation – let alone by examining DNA sequences (Hall (2000a), p. 177). This is because the formation of cell condensations is contingent not on the directives of a genetic program, but rather on the spatiotemporal state of the organism and its component parts at multiple levels (Laubichler and Wagner 2001). Gilbert and Sarkar (2000) provide additional examples of such emergent phenomena. Many evo-devoists are thus methodological antireductionists, offering the advice that we must engage in multi-leveled investigation of ontogeny and evolution in order not to miss key features of either, at micro-, meso-, and macro-levels.
- (B) – the need to focus on developmental processes – draws attention to the fundamental ontogenetic importance of epigenetics, especially given (A). Waddington, who introduced the term “epigenetics”, referred to epigenetics as the causal analysis of development (Waddington 1952; Hall 1992; Gilbert 2000). In more detailed terms, Wolf suggests that epigenetics denotes “the interactions between genes and their products, and the various other conditions composing the milieu required for developmental processes to take place. Epigenetic changes are the result of these interactions, and may contribute significantly to the phenotype” (Wolf (1995), p. 128), such that the phenotype is “the product of ontogenetic development rather than the mere consequence of the genetic constitution of the zygote” (p. 127). Variants of this latter definition are common currency in evo-devo, and some evo-devoists hold that precisely identifying types (and tokens) of epigenetic interactions is central to synthesizing development and evolution.

Especially important is the investigation of epigenetic interactions within and between modules in morphogenesis. A module is, roughly, a semi-autonomous part of an organism; modules exist at different levels of the biological hierarchy; and evolutionarily significant within-module changes can occur without disrupting the overall integrity of the organism, thereby facilitating the developmental evolution of novel characters. Bolker (2000) helpfully distinguishes between developmental and evolutionary approaches to modularity, and shows how these distinct approaches may interact and coalesce in evo-devo.<sup>7</sup>

- (C) – the belief that analysing developmental processes and mechanisms, and their evolution, improves our understanding of both development and evolution – adverts to the conviction that evolution *qua* population genetics, in presupposing development rather than investigating it, tends to miss key elements of evolution.

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<sup>6</sup> The claim that a given property could not have been explained is stronger than that it could not have been predicted, inasmuch as we can explain much that we could not have predicted (e.g., Gilbert and Sarkar (2000), p. 3).

<sup>7</sup> For discussions of modularity, see Atchley and Hall (1991), Raff (1996), von Dassow and Monro (1999), Sterelny (2000), Gilbert and Bolker (2001) and Winther (2001).

This is not simply a charge of incompleteness, but also a charge of explanatory inappropriateness. That is, while it is surely true that the roster of evolutionary change in a lineage is in some ways deficient unless it catalogues changes in developmental pathways as well as changes in adult phenotype and gene frequency in a population (the charge of incompleteness<sup>8</sup>), the further claim of evo-devoists is that the best explanation of evolutionary change is not always made exclusively in terms of changes in gene frequency in a population (just as the best explanation of some developmental mechanism is not always made exclusively in terms of changes in gene expression). Wagner (2000), for instance, has employed the concept of “explanatory force” (Amundson 1989) to indicate how, in some cases (such as the evolution of stable sex ratios), a population genetic explanation captures the relevant phenomena to be explained better than any competing explanation, while in other cases other explanations will be more appropriate. I explore both aspects of (C) in the next section.

### Development and evolution

Evolutionary developmental biologists identify two fundamental relations between evolution and development: most evolutionary changes are introduced during ontogeny, in the sense that ontogenetic modifications, and modifications in developmental processes, produce evolutionary changes; moreover, developmental mechanisms themselves evolve. In this section, I provide four examples in order to illustrate the complex interplay between development and evolution.

#### *Blind cave fish*

Consider first a case reported in a recent issue of *Science*, involving evolutionary alterations in development leading to marked heritable phenotypic change in the Mexican tetra fish, *Astyanax mexicanus*.<sup>9</sup> The fish exist in a few dozen isolated populations in northeastern Mexico; some of the fish live in streams and ponds, while others live in caves and underground pools. Over the past million years, and among other evolutionary changes, the cave fish have gone blind, while those who live above-ground continue to have large eyes. (The cave fish have also lost

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<sup>8</sup> Note that a *complete* catalogue of changes in ontogenetic pathways, adult phenotype, and gene frequency in a population is practically impossible for most lineages (possibly excepting fruit flies, bacteria, and viruses). The goal of a response to the charge of incompleteness then must not be (in the case of most lineages) completeness as such, but rather non-arbitrary representativeness; that is, proffering a representative catalogue of evolutionarily significant changes at multiple levels should be considered an appropriate, tractable response to the charge of incompleteness. Amundson (2001) offers a helpful critical analysis of the charge of completeness.

<sup>9</sup> I thank Brian Hall for bringing this case to my attention. Hall thinks that the results are provocative, though he is careful not to read too much into findings regarding only a single species. See his remarks in Vogel (2000), at p. 2120. For details about the case, see also Yamamoto and Jeffrey (2000), Pennisi (2000); for a comprehensive review of the evolution and development of the cave fish, see Jeffery (2001).

pigmentation, while the surface fish have not.) While eye development starts off in the usual way in the cave dwellers, producing a rudimentary lens and optic cup, after twenty-four h the cells in the embryonic lens die, the cornea and the iris fail to develop, and the retina does not organize into distinct layers. Eventually, the eyeball sinks back into the skull and is covered by a skin flap. Yamamoto and Jeffrey (2000) were able to show that the lens is responsible for promoting eye development, as a cave fish embryo which, at twenty-four h of age, has had the lens vesicle of a surface-dwelling conspecific transplanted into its optic cup, develops a large eye with a distinct pupil and a properly developing retina; its other, untreated eye, sinks into its orbit. Thus, “a surface fish lens can induce the development of anterior eye parts that have been lost during cave fish evolution” (Yamamoto and Jeffrey (2000), p. 631).

So, loss of eyes in *Astyanax* occurs by disruption of the developmental pathway at a specific point, and it is possible to rescue eyes by providing a signal at the right time and place, for no genetic potential has been lost. Invoking the developmental phenomena, in addition to ecological and population genetic aspects, thus helps to complete (through complementarity) the explanation of the evolution of these two tetra fish morphs; but, more importantly, it evinces the interrelations between development and evolution now reclaiming popular attention among both biologists and philosophers.

Jeffery has recently argued that these cave fish are an excellent model system for evo-devo, not least because, since cave fish descend from their surface-dwelling conspecifics, we already know the direction of developmental change, which makes for an easier reconstruction of the evolutionary history of the cavefish (Jeffery (2001), p. 2). Moreover, studies of cave fish in relation to surface fish highlight “the possible role of tradeoffs between constructive and regressive processes” in evolution and development (p. 9). But much work remains to be done. For instance, it has been suggested that the cave fish have ‘traded in’ their eyes – which are not needed in the underground streams, and so their retention is not subject to evolutionary pressures – for other, more adaptive features, as the troglodytic fish have more teeth and taste buds than their surface-dwelling conspecifics (Vogel (2000)). It is possible (even likely) that the surface-dwelling, large-eyed fish are developmentally precluded from evolving improved gustatory and masticatory apparatuses; such a result, if it can be established, would be important in showing how development biases evolutionary outcomes, prompting a creep along the continuum of synthesizing scenarios from far right to middle. Yet if the surface-dwelling morph’s variability is not biased against or away from this innovation, we are nonetheless not forced to resign ourselves to the right end of the continuum, for the developmental and evolutionary co-production of cave-fish blindness remains evolutionarily significant, and demands joint developmental and evolutionary explanation.

#### *Butterfly wing morphology*

Consider next the development and evolution of eyespot patterns on butterfly wings.

Eyespots are a relatively recent innovation, and they are important in predator avoidance as they direct attention away from vital organs.<sup>10</sup> One recent suggestion within evo-devo is that “the development of eyespots is induced by a small group of cells, the eyespot organizer, which cause[s] the surrounding cells to synthesize pigments” (Wagner (2000), p. 96; the relevant work was carried out by Keys et al. (1999)). The eyespot organizer appropriates specific molecules involved in establishing the basic wing plan of the butterfly – in particular, the anterior-posterior boundary – and attaches to them additional regulatory functions, from which the changes in butterfly wing morphology follow. A population geneticist would explain the emergence of eyespots in terms of a genetic change in the population, tracked by the selection of mutant alleles responsible for the new patterns. But while it may very well be true that one or two mutations are involved, “to state that a genetic mutation led to a favored character, which, in turn, was selected is utterly uninformative in explaining innovation” – not least because “the emergence of morphological innovations depends to a large extent on the epigenetic dynamics of the involved developmental pathways” (Wagner et al. (2000), pp. 822–823; see also Pigliucci and Schlichting (1997) and Newman and Müller (2000)).

That the population geneticist is mute regarding the developmental biology of an evolutionary change does not make the population geneticist’s explanation wrong; it rather shows that the evo-devo explanation is both more complete and more appropriate (has more explanatory force) in this context. For without detailed knowledge of the developmental interactions between genes and proteins involved in establishing the anterior-posterior boundary in *Drosophila* and butterfly wings, “it would have been impossible to understand which genetic changes were sufficient to establish an eyespot organizer” – the evolutionary innovation of interest (Wagner (2000), p. 97). In other words, though the evolutionarily significant change may well be tracked at the genetic level, the change occurs within a developmental mechanism inaccessible (and of little interest) to the population geneticist. Evolutionary innovations, especially in morphology, have been something of a mystery to evolutionary biologists (Mayr 1960), but are much more straightforward when examined developmentally.

#### *External furry cheek pouches*

Consider next the origin of fur-lined external cheek pouches in geomyoid rodents, mainly pocket gophers and kangaroo rats (Brylski and Hall 1988a, 1988b). Other rodents have cheek pouches internal to the mouth, which are lined with buccal epithelium; in contrast, geomyoid rodents have cheek pouches opening outside the mouth, which are lined with fur. Both types of cheek pouches are used to store food obtained during foraging, though external pouches may be both larger and more efficient at conserving body water than internal pouches. Drawing on developmental

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<sup>10</sup> I borrow this example from Wagner (2000), pp. 96–97, who discusses the work of Keys et al. (1999). For more on the relationships between evolution and development in butterfly eyespots, see Brakefield et al. (1996), Nijhout (1996), Brakefield and French (1999) and Brakefield (2001).

data, Brylski and Hall have shown that internal pouches are the ancestral condition; that is, the evolutionary ancestors of living geomyoids had internal cheek pouches. Moreover, the external cheek pouch arose during ontogeny from the buccal epithelium (which lines the internal cheek pouches of ancestral and other rodents). The developmental mechanism is a common one, epithelial evagination, during which the epithelium takes up a new position and participates in new interactions. In the case of the genesis of the external cheek pouch, the evagination begins at the corner of the mouth, which (uniquely in geomyoids) participates in the evagination; Brylski and Hall showed that the novel external pouch is the result of a small shift in the location and magnitude of the evagination to include the lip epithelium at the corner of the mouth. As the lips develop in tandem with the growth of the snout, the evaginated corner of the mouth is transformed into the opening of the external pouch.

Brylski and Hall speculated, with good reason, that the external pouch was not originally lined with buccal epithelium (as in internal pouches) and then only later became furry; instead, the furriness of the external pouch was the “direct result of pouch externalization due to an inductive interaction resulting from the novel juxtaposition of the pouch and facial epithelia” (Brylski and Hall (1988a), p. 394). That such a small change in a developmental mechanism can have such a dramatic effect, coupled with the fact that no living geomyoids have both internal and external pouches, suggests that there is no intermediate ancestor between rodents with internal and rodents with external pouches. (It would be difficult, both developmentally and functionally, to have both internal and external pouches.) So changes in developmental mechanisms may produce coordinated change and thereby participate in the evolution of a lineage; in other words, development may drive evolution by providing the material basis for a new structure. Again, we see the complex interplay between development and evolution.

#### *The developmental origins of the turtle shell*

Two recent publications underscore the crucial role of changes in development in the generation of the turtle shell as an evolutionary novelty. For details of the anatomy of the turtle shell, see Gilbert et al. (2001) and Rieppel (2001). For our purposes, only a few general observations are required: first, turtles’ ‘dermal armor’ comprises a carapace covering the back of their trunk, and a plastron covering their belly; and secondly, the shoulder blade (scapula) of turtles – uniquely among tetrapods – resides within the rib cage.

New evolutionary developmental studies have mortally weakened the widely held hypothesis that the turtle shell arose gradually, through the accretion of small changes in development, an hypothesis already struggling from its lack of fit with the fossil record and with molecular data. Rieppel (2001) can now claim that the gradualistic model is not compatible with the development of turtles, as shown by Burke (1991) and Gilbert et al. (2001). Gilbert et al. (2001) were able to confirm that the scapula of the turtle develops within the rib cage as a function of a deflection of rib growth to a new position, and this is likely the result of an inductive

interaction within the so-called carapacial ridge (CR). The outer edge of the carapace eventually forms from the CR, which arises in the early embryo dorsal to the limb buds on the lateral surfaces. Turtles' ribs develop laterally, rather than ventrally, due to the CR; when the CR is either surgically removed or prevented from forming, rib morphogenesis occurs as it does in non-turtle (in fact, non-chelonian) vertebrates (Burke 1991).<sup>11</sup> These are, Rieppel asserts, the only two possibilities: either ribs develop deep or superficial to the scapula; moreover, "there are no intermediates, and there is only one way to get from one condition to the other, which is the redirection of the migration, through the embryonic body, of the precursor cells that will form the ribs" (Rieppel (2001), p. 991). As Gilbert *et al.* note, the carapacial ridge forms through the thickening of the ectoderm "underlain by condensed mesenchyme", which is a typical configuration for epithelial-mesenchymal interaction (2001, p. 49). The CR is responsible for the redirection of cell migration, and the direction of turtle development along a new path.

A simple epithelial-mesenchymal interaction at the onset of carapace development "provides a basis for hypotheses about the rapid evolution of this [the turtle] body plan" (Gilbert *et al.* (2001), p. 56) – namely, that the turtle body plan arose at once rather than gradually and stepwise. Rieppel (2001, pp. 990–991) considers this a vindication of Étienne Geoffroy Saint-Hilaire's 1833 assertion that a small change early in development could have major effects not only developmentally but also in evolution (though Rieppel rhetorically situates his discussion in terms of Goldschmidt's saltational thesis of "hopeful monsters"). At any rate, the evolutionary biologist's decisions about how to explain evolutionary ancestral relationships and the origins of developmental novelties cannot (always) be made without recourse to the details of development.

These latter examples force us leftward, toward the middle of the continuum diagrammed in Figure 1; that is, toward evo-devo. It is not always appropriate to presuppose reliable development in a theory of evolution, for developmental mechanisms themselves evolve (or are conserved) through evolutionary time, and evolution and development are mutually constrained by the other. Even if our aim is to understand evolution alone, and development evolves, then evolutionary biology must go well beyond the Modern Synthesis (and it has) in order to explore the phylogenetic implications of development.

### **Developing evolution**

Thus far, then, Sterelny and I are more or less in agreement, in that we both recognize (and, I think, appreciate) the impulse toward some version of evo-devo. In the remainder of this article, I explore some differences between our respective views.

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<sup>11</sup> Experimental work on the causal role of the CR in the placement of the ribs was conducted by Burke (1989, 1991) – who also coined the term, 'carapacial ridge'.

Sterelny suggests that the required changes to Neo-Darwinian evolutionary theory (in particular) are easily made, if not already part and parcel of the Neo-Darwinian perspective. He concludes his article with the following claim: “I do not see any fundamental conceptual problem for evolutionary biology on any of the three [surveyed] views” (Sterelny (2000), p. S386). The idea seems to be that, as long as we strive for completeness in our explanations, and so recognize that evolution is a two-step process – developmental introduction of variation (e.g., a phenotypic novelty) followed by selection and a change in gene frequency in the population (West-Eberhard (1998), p. 8419) – then evolution and development are straightforwardly synthesized.

I submit that Sterelny is mistaken, and that his mistake is complex. First, we must parse the meaning of “fundamental conceptual problem”. Does “fundamental” modify “conceptual problem”, or is the problem one of “fundamental concepts”? If the former (what I shall call the fundamental *conceptual problem*), then Sterelny’s conclusion is wrong even by his own lights. If the latter (what I shall call the *fundamental conceptual problem*), then Sterelny’s conclusion does not follow for other reasons to be addressed below.

Consider the fundamental *conceptual problem* first. Sterelny argues that two of the scenarios he surveys, those at the right end of the continuum in Figure 1, are relatively untouched by the developmentalist critique. Recall that Sterelny also sketches another scenario, his account of evo-devo, falling at the middle of the continuum, according to which the focus of evolutionary biology changes from the study of adaptation as such to the study of evolvability, or the ability of an organism to generate (adaptive) variability (see, e.g., Kirschner and Gerhart (1998)). In outlining the nature of the problem of evolvability, Sterelny draws on work in evo-devo on highly conserved elements of development (such as the homeobox genes<sup>12</sup>) and on the phenomenon of modularity. Development is modular if traits or trait complexes develop relatively independently of one another (Sterelny (2000), p. S381). Though presumably aware of other main thrusts of evo-devo as explored in the foregoing sections, Sterelny presents a version of evo-devo the shape of which is delimited almost exclusively by the concepts of modularity and evolvability. His argument is that if evolvability can be explained, then “explaining adaptation would be relatively straightforward” (Sterelny (2000), p. S377).

I shall grant Sterelny’s account of evo-devo, for the sake of argument, but only to conclude that if synthesizing evolution and development leads to changing the basic *explanandum* of evolutionary theory – what Sterelny calls “evolution’s ‘hard problem’” ((2000), p. S376) – from adaptation to evolvability, then that is symptomatic of a fundamental *conceptual problem* posed to evolution by development. So perhaps Sterelny is prognosticating instead that there are no *fundamental conceptual problems*.

If Sterelny means to imply that no fundamental concepts will be *eliminated* in the synthesis of development and evolution, then I am sympathetic, for core evolution-

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<sup>12</sup> See Robert (2001) for a philosophical analysis of the role of homeobox genes in development and evolution.

ary concepts – such as variation, adaptation, fitness – surely remain integral to evo-devo. But if Sterelny means that these concepts undergo no fundamental revision, then his evo-devo is not my evo-devo. In other words, evo-devo fills a wider swathe of the middle-ground (and more dimensions of it) than Sterelny implies.

Population-geneticist-*cum*-evo-devoist Arthur (2000) has recently suggested that there are five lacunae in Neo-Darwinian evolutionary theory: [1] it omits all intervening (developmental) steps between mutation and selection; [2] its almost exclusive focus on selection (which is “destructive”) neglects the creative generation of variation (in development and otherwise); [3] it may forswear developmental stability in favour of evolutionary change; [4] in its preoccupation with how organisms respond to environmental problems, it is externalist; and [5] in its extreme formulations, it is exclusively gradualist. Arthur suggests that the turn to evolutionary developmental biology closes these gaps in two ways: by redirecting attention to what is standardly ignored, assumed, backgrounded, or blackboxed, and, *pace* Sterelny, by revising the core concepts of Neo-Darwinian evolutionary theory. (Insofar as evolutionary theory is not exclusively Neo-Darwinian, some of the required revisions may be minor by comparison, though Sterelny does have Neo-Darwinism in mind.)

Gaps [1] and [2] *may* be filled relatively straightforwardly as Sterelny imagines, provided that evolutionary biologists are willing to open the developmental (epigenetic) box and explore the manifold ways in which ontogeny impinges on phylogeny. This is not a matter of merely admitting that epigenetic processes occur in development, but rather of exploring how these processes are crucial to understanding evolution (as in the four examples explored above).

Weiss and Fullerton (2000) offer a radical perspective on how a focus on epigenetics may enrich the study of evolution in developmental context. They suggest that we consider “that it is *not* the genome that is especially conserved by evolution. Suppose the ephemeral phenotype really *is* what we need to understand and what persists over time. Genes would then be ‘only’ the meandering spoor left by the process of evolution by phenotype. Perhaps we have hidden behind the Modern Synthesis, and the idea that all the action is in gene frequencies, for too long” (p. 192).<sup>13</sup> Since “evolution works by phenotypes, whole organisms, not genotypes”, the Neo-Darwinian account of what evolution *is* would require substantial conceptual overhaul (p. 193).

Filling gap [3] requires attention to the interplay between stasis and change, as well as detailed analysis of developmental constraints biasing phenotypic outcomes (as in the example of the blind cave fish; for more on these themes, see Fusco (2001)). Sterelny correctly suggests that developmental constraints already form part of mainstream evolutionary theory (toward the right end of the continuum), but

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<sup>13</sup> See also Newman and Müller (2000) and Robert (2001). Note that palaeontologists have known this all along, in that palaeontologists have historically “seen” only the phenotype. This helps to explain why the theory of punctuated equilibrium originated within palaeontology and not elsewhere. Thanks to Wendy Olson for this observation.

given Amundson's (1994) discussion of the substantial differences between constraints on adaptation (attended to by evolutionary biologists) and constraints on form (attended to by developmental biologists), we should be wary of the latter being ignored in favour of the former (see note 2, above). Sterelny himself speaks of constraints on variability, a formulation which threatens to collapse Amundson's useful distinction (see also von Dassow and Monro (1999), p. 312). (It is worth noting that the long-term stasis implied by Eldredge and Gould's theory of 'punctuated equilibrium' (1972) is a nice example of how modern evolutionary theory already accounts for evolutionary [and developmental] stability – but the theory still tends to generate hostility, though Dawkins (1986), Dennett (1995) both believe it is part and parcel of the Neo-Darwinian synthesis.)

The fourth and fifth gaps may be more problematic for Neo-Darwinians. Arthur's version of *evo-devo* corrects for [4] by redirecting evolutionary attention to both the insides and the outsides of organisms. The usual Neo-Darwinian story is that "the environment imposes a set of adaptive demands on a population, and selection shapes that population so that it meets those demands increasingly well" (Sterelny (2000), pp. S372–S373). This Neo-Darwinian picture of mutation-variation-selection is externalist (even though mutations are surely internal!): successful variants are those that respond well to external pressures exerted by environments.<sup>14</sup> But this picture ignores the developmental intermediaries between mutation, the production of variation, and the sieving process of selection, and also presumes *a priori* that genetic mutation is the ground of all evolutionary change. In contrast, Arthur (1997) and Fusco (2001), for instance, maintain that an organism's internal structures and developmental interactions may be positively favoured by selection. Evolution is not exclusively about how well organisms fit external environments which putatively pose problems for organisms to solve, but also how well an organism's insides fit together: how well it is internally integrated (which may or may not assist in responding well to external pressures). Darwin knew this, as did Fisher, Wright, and Haldane, but present-day Neo-Darwinians know it not – the fallout of blackboxing development, in fact, of blackboxing the organism (Shishkin 1992). But even should the black box be opened, overcoming the externalism of evolutionary theory will represent a challenge; at the least, it will require re-interpreting the scope of adaptation and selection.<sup>15</sup>

What of the fifth gap? To Neo-Darwinians, this putative "gap" is in fact a virtue. The Modern Synthesizers were, of course, expressly committed to gradualism: evolution occurs by the accretion of minute adaptive changes, and speciation occurs

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<sup>14</sup> Sterelny has suggested (personal communication) that Neo-Darwinians explore numerous non-externalist (though not obviously internalist) aspects of evolution, such as sexual selection and frequency-dependent selection. Pigliucci and Schlichting (1997), pp. 147, 151 argue that quantitative geneticists' assumption of a constant fitness landscape ignores frequency-dependent selection. At any rate, the existence of such putative exceptions as Sterelny identifies makes Neo-Darwinism not *exclusively* externalist, though it may still be *excessively* externalist, in which case Arthur's complaint holds.

<sup>15</sup> Shishkin (1992) goes further still, urging that we understand evolution as "a transformation of integral properties of the developmental system" in establishing developmental stability (p. 37).

by mega-accretion. But many evolutionary biologists (those who would consider the Neo-Darwinians to be on the extremist fringe) already acknowledge that there are exceptions to micromutational gradualism, as in the evolution of basic body plans (and not only in the case of turtles – see, e.g., Raff (1996), Arthur (2000, 1997), Robert (2001)). A shared objective of evolutionary developmental biologists and many evolutionary biologists proper is to secure a firm place in evolutionary theory for such putative exceptions. For evo-devoists, the question of the nature of mechanisms of macro-evolution is an open one; Stern (2000) has recently shown that analysis of development may be ineliminably important in deciding between competing evolutionary hypotheses regarding micro- vs. macro-mutational evolution. Focusing on evolvability should be of distinct usefulness here.

Given the conceptual retooling required to repair these lacunae, and the changes in theory-building and experimental design necessary to fully realise the promise of evo-devo, development surely does pose *fundamental conceptual problems* for (at least Neo-Darwinian) evolutionary theory. But – my own optimistic conclusion – these problems are by no means intractable, as the current success of evo-devo explanations attests.

## Conclusion

In the title of this article, I raise the question, ‘how developmental is evolutionary developmental biology?’ I submit that if we take Sterelny’s view as accurate, then we must respond ‘not very’. This is because Sterelny’s version of evo-devo attends insufficiently to the fundamental problems of development (growth and change) in relation to evolution. If, however, we engage a broader account of evo-devo, then we might answer more positively. (Taken to its logical conclusion, this might imply that Sterelny and I are talking past each other, me about evo-devo and he about devo-evo; if that is true, then perhaps my argument here is in favour of evo-devo over devo-evo rather than of one account of evo-devo over another. Again, I cannot resolve this issue here, but leave it to others, or to another time.)

I am obviously somewhat less sanguine than Sterelny about the relations between evolutionary theory and the phenomena of development. Despite a long history of efforts, I agree that it is only in the past decade that we have begun to taste the fruits of evolutionary and developmental biology synthesized. One reason for the delay is that neither fits the other very well: efforts simply to “accommodate” development within Neo-Darwinian evolutionary theory were (and are) bound to fail: genuine synthesis – not accommodation, not subsumption, – ought to be our goal. Evo-devo is as successful as it is fundamentally because it is a *synthesis* – it does not attempt to accommodate development within evolutionary biology, or *vice versa*, but rather brings developmental and evolutionary biology together in a new discipline. So evo-devo does not spell an end to either evolutionary or developmental biology proper, but makes room for them to interact fruitfully, even synergistically, and to uncover phenomena and explanations inaccessible to either evolutionary or developmental analysis alone (see also Wagner et al. (2000)).

But considerable work remains to be done: despite my intimation of ‘happiness ever after’, evolutionary developmental biology is not unassailable. In evo-devo, as both evolutionary biology and developmental biology undergo some changes, neither is quite what it once was, and together they are not quite yet what they could be. Resolving this problem may indeed turn on empirical work, as Sterelny suggests, but theoretical and conceptual analysis will remain critically important.

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