Epistemological and Practical Aspects of the Developmental Synthesis: Streamlining the Naturalistic Agenda

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1. Introduction

"Darwinian evolutionists," Ernst Mayr boasts in his latest delivery, "have every reason to be proud of the paradigm of evolutionary biology that they have constructed" (Mayr 2001: 272). Challenges to the Darwinian paradigm were pronounced by numerous authors. Most notoriously, students of macroevolution have questioned the assumption of gradualism that underlies neo-Darwinism, and neutral evolution and morphogenesis were claimed to contradict it. But these and other attempts to "refute" one or the other assumption of modern evolutionary theory — the foundation and point of convergence of most of the biological disciplines in the last fifty years — have all been "invalidated," Mayr assures us.

The success story of the Modern Synthesis is being told and retold by both the popular scientific media and the professional Darwin industry every day — literally (see Depew and B. Weber 1995, Smocovitis 1996, and M. Weber 1998 for critical assessments).[1] Yet there is a growing sentiment that extant evolutionary theory, in which the reigning mode of explanation is genetic and adaptationist, represents an "unfinished synthesis" (Reid 1985). Current calls for a "New Evolutionary Synthesis" that would genuinely incorporate development (Gilbert 2000: 703—705), or for a straightforward "Developmental Synthesis" (Amundson 1994), revive Waddington's life-long attempts to forge a final synthesis between embryology and evolution. Evo-devo, broadly conceived, begins to address seriously Victor Hamburger's (1980) early complaint that the Modern Synthesis treated the processes of ontogeny as a "black box." Gene-centered biology comes dangerously close to — officially long rejected — preformationism. Under the impression of the close mapping between genotype and phenotype in many kinds of modern organisms, it takes an organism's morphological phenotype to be "determined" by its genotype, and portrays the development of individual organisms as the unfolding of a "genetic program" alleged to reside in the fertilized egg (for critical assessments, see, e.g., Atlan and Koppel 1989, Rose 1998, and Moss 2002).[2] Yet, as one dissenter puts it, "the organism does not compute itself from its genes. Any computer that did as poor a job of computation as an organism does from its genetic 'program' would be immediately thrown into the trash and its manufacturer would be sued by the purchaser" (Lewontin 2000: 17). The evolutionary-theoretical version of the genetic program notion usually remains unchallenged even in glosses on neo-Darwinism that otherwise disagree over such issues as the tempo and mode of phenotypic evolution, the degree to which genetic change can result from selectively neutral mechanisms, and the universality of adaptation in accounting for complex traits.

Although life did not require DNA to get started (see, e.g., Goodwin 1994:168—175 for a brief review of theories of the emergence of order), it has long entered a regime in which genes have become necessary for both development and evolution (Maynard Smith and Szathmáry 1995, ch. 6).[3] The

official *interactionist consensus* (Robert 2002, ch. 2) pays lip service to the realization that genes alone are insufficient for developmental agency (see, e.g., Gray 1992 and Moss 2002 for forceful arguments to this effect), and that both genes and *environments* are required for the production of phenotypes. But the dominant view still largely disregards the generative (and hence explanatory) roles the phenotype *per se* plays in many developmental and evolutionary phenomena of interest to biologists. This is true in at least two important ways:

(i) At the developmental level, there are no good reasons to assume that informational models according to which all the relevant information resides in the genomic DNA suffice to capture all or most of the old or new developmental data at hand (cf. Sarkar 2000). Causal analysis, taking fully into account epigenetic and environmental determinants, remains as indispensable as ever — remember *Entwicklungsmechanik* (Müller 1994)!

(ii) A similar limitation exists at the evolutionary level, where a full understanding of selection requires that we capture the regulatory phenotypic structures and functions of species. Again the informational picture must remain incomplete. "One can construct mathematical 'laws' of genetics within the information picture, but one cannot assert that they apply, nor understand the limits of their application, nor understand the alternative possibilities where their application breaks down, without recourse to the details of the causal picture" (Hahlweg and Hooker 1989: 85—86). To evolutionary biologists, the emerging understanding of developmental mechanisms is "an opportunity to understand the origins of variation not just in the selective milieu but also in te variability of the developmental process, the substrate for morphological change" (von Dassow and Munro 1999: 307). *Note that the great debates within evolutionary biology focus in part on the causal mechanisms* of evolutionary change rather than on the elucidation of particular phylogenetic relationships (Atkinson 1982). Opposing developmental biology to evolutionary biology in terms of causal versus functional explanation, then, would certainly be an oversimplification.

"Dawkinspeak" has by now become so prevalent in the media-impregnated Western culture that it may no longer be trivial to point out that, for instance in the case of our own species, there simply *aren't enough genes* to determine behavior in the simplistic ways presented by many behavioral geneticists and evolutionary psychologists, among others (Ehrlich 2000). Even Mayr, whose confidence in the power of molecular biology to explain the whole of life is unshaken, admits that because of pleiotropy, polygenism, and the unity of the genotype, "the study of phenomena such as evolutionary stasis and the constancy of body plans is so refractory to analysis" (Mayr 2001: 273; cf. Maynard Smith 1998).

It may be too early to say how modest or revolutionary the changes in our thinking about evolution occasioned by evo-devo will be. But it is certainly timely to observe the profoundly paradoxical nature of the gene-centrism that

characterizes the currently dominant evolutionary paradigm. Its fatalist view of phenotypes as “vehicles” that are the prisoners of their genes (Dawkins’ “lumbering robots”) reigns supreme at a time when the genomes of plants, animals, and increasingly also humans are dramatically transformed in the name of health, economic profit, or other cultural aims. This novel situation radically contradicts some of the founding principles of ultra-Darwinian molecular biology, such as the "Central Dogma." Yet without the practical application of these very principles, our new, "post-genomic" cultural predicament could not have arisen! There is much to be said, then, for Tibon-Cornillot’s (1992: 17) diagnosis of this paradox as a crisis of the neo-Darwinian paradigm.

In this paper we will sketch some of the major features of our own *organic systems approach (OSA)* to evolutionary developmental biology (evo-devo) and explore its potential to contribute to the Developmental Synthesis that progressively takes shape. Our central concerns are the generic, conditional (i.e., unprogrammed), "pre-Mendelian" *generation* of primordial organismal form and structure, and evolutionary *innovation*: how novel elements arise in body plans (section 4). Contrasting OSA with some of the more radical approaches to evo-devo, such as process structuralism and developmental constructionism, will make clear that a naturalism that is nonreductionist and yet profoundly committed to causal-mechanistic explanation is the philosophical metatheory that best fits evolutionary developmentalism. As a package deal, the evo-devo-naturalistic account allows to turn the tables on the adaptationist, gene-centric view and take seriously again Walter Garstang’s dictum (in 1922) that ontogeny does not recapitulate phylogeny, but rather *creates* phylogeny (Gilbert 2000: 703). More specifically, in Løvtrup’s (1984: 261) words: “Inverting Haeckel’s biogenetic law, we may assert that ontogeny is the mechanical cause of phylogeny. And it must be so, for ontogeny is a mechanical process, while phylogeny is a historical phenomenon.“ To round off, we will discuss some epistemological and practical issues issues involved in the Developmental Synthesis, such as the kind(s) of unification that are at stake in relation to the data- and technique-driven nature of most current research, and list a number of issues that we feel should become more prominent on the agenda of philosophers of biology (section 5).

To set the scene we consider some of the requirements for evo-devo to become a mature scientific discipline (sections 2 and 3).

2. A new subdiscipine of biology?

Reflecting on the renewed interest in the relationship between evolutionary biology and developmental biology that awoke in the 1980s, Atkinson (1992: 93) speculated that their reunion “may result in a new subdiscipline of biology, if there is a set of unique concepts and methods which tie the various research approaches together.” We discuss concepts and methods in turn and add two

more issues: the explanatory strategies of evo-devo and what we dub "evo-devo package deals.".

(1) Elements for a conceptual framework for evo-devo

Anticipating current attempts to delineate evo-devo from more established research in developmental biology and evolutionary biology (Gilbert, Opitz, & Raff 1996; Hall 2000; Raff 2000; Wagner, Chiu, & Laubichler 2000; Robert, Hall, & Olson 2001), Atkinson suggested that concepts such as *bauplan* (Riedl 1978), *canalization* (see, e.g., Gibson and Wagner 2000), and *developmental constraints* (see section 2) may serve in such a capacity. Today we should add *evolvability* — the inherent potential of certain lineages to change during the course of evolution[4] — *and developmental modularity* in the sense of compartmentalization (Wagner 1996; Callebaut and Rasskin-Gutman 2002; Schlosser and Wagner 2002) to his list.

Most importantly from our perspective, we should add *evolutionary innovation* (Müller 1990; Müller and Wagner 1991; Müller 2002a; Müller and Wagner 2002), the *origination of form* (Müller 1990; Wagner and Altenberg 1996; Newman and Müller 2000, 2002; Müller and Newman 2002), and the central role *homology* (Wagner 1995, 1996; Müller and Newman 1999; Laubichler 2000; Müller 2002b) plays in origination and innovation.

We expect that investigations of developmental constraints, evolutionary innovations, and the evolution of development in general will turn out to be the most genuine contributions of evo-devo, whereas homology assessment and the explanation of the developmental architecture of adaptations, however important per se, are likely to remain ancillary contributions to existing research programs (Wagner, Chiu, and Laubichler 2000).[5]

This much being said, it should be granted that evo-devo is still in search of a clear conceptual framework in which the aforementioned concepts (and related ones) can be integrated in a logically coherent and (cautiously) parsimonious way. A first necessary step in this direction may be to elucidate what specifically constitutes a *developmental mechanism* (von Dassow and Munro 1999). Becoming more clear on what the proper goals of evo-devo should be is another urgent desideratum, and may be actually be easier than one would expect (Wagner, Chiu, and Laubichler 2000; Robert, Hall, and Olson 2001).[6]

(2) Evo-devo methods

Comparative developmental biology, experimental developmental biology, and evolutionary developmental genetics are the methods most commonly relied on in evo-devo. These methods clearly are not *unique* to evo-devo, and one should not assume that their combined application will automatically yield unproblematic, novel results (cf. von Dassow and Munro 1999). When Haeckel proposed his

views on recapitulation, the union of evolution and development he envisaged was primarily one of *descriptive* sciences. For Haeckel, as for Darwin before him, comparative embryology served as the source of knowledge in the construction of phylogenies (see, e.g., Richards 1992, 2002). Although the *nexus* between development and evolution may to a large extent remain descriptive (Nijhout 2002), developmental biology (e.g., Hall 1992/1997, Gerhard and Kirschner 1997; Gilbert 2000) has come a long way and today offers a wealth of causal-mechanistic theories and models — also, but not only, because it has become molecular (Robert 2001; Sarkar 2002).

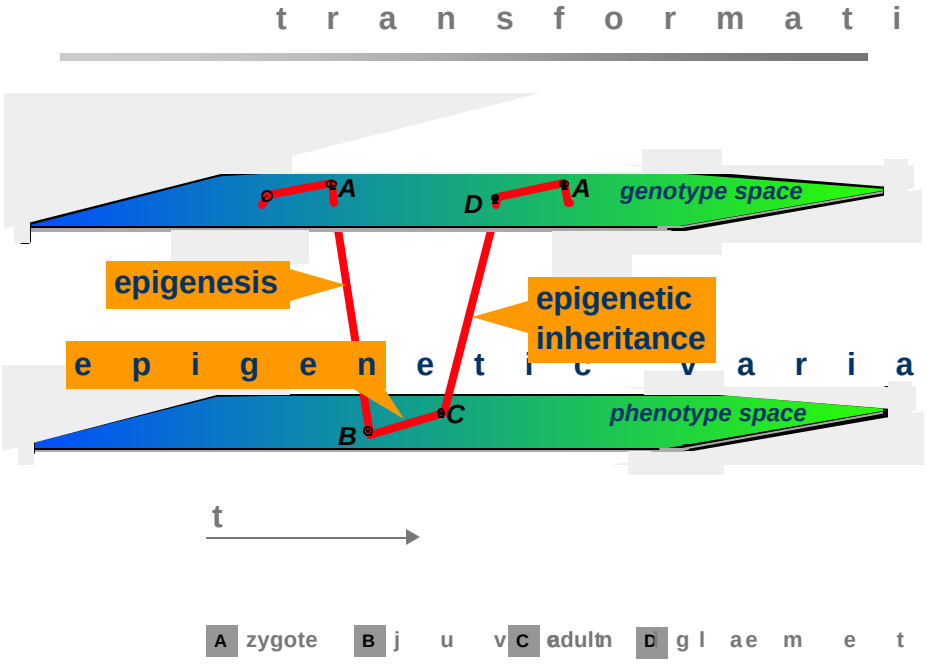


Fig. 1. Four transformations (Müller, after Lewontin):

A-B transformations on the way from zygote: juvenile (development)

B-C transformations acting on the gene pool of a population, influencing the genetic information present in reproducing adults (selection, drift)

C-D transformations during the production of new gametes (meiosis)

D-A transformations affecting recombination of the gametes to form a new zygote (recombination)

Evolutionary-developmental epigenetics comprises the study of epigenesis (cf. Fig. 2), epigenetic gene regulation, epigenetic variation, and epigenetic inheritance

Biologists had long recognized that the evolvability of development is the key to morphological evolution, but only now does molecular genetics produce substantial characterizations of developmental regulatory processes that make it

possible to analyze them comparatively. Are there — or for that matter, *should* there be — methods that single out the evo-devo enterprise? In an attempt to zero in on the role of developmental mechanisms in evolutionary processes, and in particular evolutionary innovations, Wagner, Chiu, and Laubichler (2000) propose a checklist for establishing a causal link between molecular developmental evolution and phenotypic evolution: (i) What is the developmental mechanism that accounts for the derived character (-state)? (More specifically, does the identified mechanism account specifically for the derived character state, or is it responsible for more fundamental and more ancient, plesiomorphic, character states within the lineage?) (ii) Does the developmental mechanism for the derived character (-state) map to the same node on the phylogeny as the derived character (-state)? *Coincidence* is the first test of the causal efficacy of the mechanism in the evolutionary process. Only mechanisms that were active in the ancestor can account for the evolutionary origin of the character. The test may be difficult because of the *recency bias* of character reconstruction. (iii) What are the developmental changes that occurred at the origin of the derived character (-state)? As Wagner et al. state, in general the study of the sequence evolution of developmental regulatory genes is a powerful tool for detecting candidate mutations that may be responsible for developmental and phenotypic transformations; yet this method has its inherent limitations (cf. the next section). (iv) Are the genetic differences sufficient to cause the derived character (-state)? Advances in transgenic technology "make the tought of performing these experiments less crazy than they were a few years ago" (p. 828).

If all the answers to these questions support a hypothesis about the developmental mechanism for the origin of a novel phenotypic character, the conclusion "is all but unavoidable that this mechanism in fact was instrumental in causing the origin of the derived character (-state). We take it that what we dub *evolutionary developmental epigenetics* (Fig. 1) is as relevant here as the more familiar evolutionary-developmental genetics (see section 4 for instantiations).

(3) The explanatory strategies of evo-devo

From an epistemological perspective, what current evo-devo seems to be largely lacking is a way to get from the knowledge of parts (entitities and their properties) and what they do (process, activity) — knowledge that a field like developmental genetics increasingly provides — to a full-fledged, formal understanding of developmental phenomena. "Mechanism, per se, is an explanatory mode in which we describe what are the parts, how they behave intrinsically, and how those intrinsic behaviors of parts are coupled to each other to produce the behavior of the whole" (von Dassow and Munro 1999: 309). This common sense definition of mechanism implies an *inherently hierarchical decomposition* (ibid.; cf. Machamer, Darden, and Craver 2000: 13—18) which, historically, has been unattainable to developmental biologists as their knowledge of the parts was insufficient. Instead, for explanation we still rely primarily on a sort of *local causation*: "The operational approach of developmental genetics, for instance,

takes for granted the organism as a working whole, with no general assumptions about the nature of developmental mechanisms beyond the empirical fact that some fraction of mutations have discrete, visible effects. Developmental genetics begins with an induced anomaly (a mutation) and a (hopefully discrete) consequence, then proceeds to decipher a perturbation-to-consequence chain" (von Dassow and Munro 1999: 309). This kind of account allows a description of what parts (genes and their products) do to *each other*, but it "doesn't articulate any sense of the mapping from genotype to phenotype, which is what we ultimately want" (ibid.). We discuss the prospect for a more integrative causal explanation of evo-devo phenomena in Callebaut and Müller (2002).

(4) Evo-devo package deals

Our discussion up to now may have suggested that evo-devo is more monolithic than it actually is. In fact, various accounts of evo-devo exist, which in part compete with each other (Table 1). Although the temptation to cluster them further is great (here one can think of, for instance, Goodwin's vindication of Kauffman's nonlinear models, or DST's tendency to portray Lewontin's work as belonging to DST, or the suggestion that GE provides DST with an "engine"), the conceptual, methodological, and philosophical differences between these several approaches remain considerable. We feel that in this incipient stage of the articulation of evo-devo it is probably wiser to cherish and cultivate this intellectual (and social!) variety than to apply Occam's razor savagely.

A further complication arises from the circumstance that not merely competing *theories*, but much broader theoretical and empirical perspectives are at stake here. Approaches to evo-devo such as developmental or "process" structuralism (e.g., Ho and Saunders 1979; Goodwin et al. 1983: Goodwin 1994), self-organization (e.g., Kauffman 1993), the dialectical account (Levins 1968; Levins and Lewontin 1985; Rose 1998; Lewontin 2000), or developmental systems (e.g., Oyama 1985, 2000; Gray 2001), are typically presented as “package deals” that not only include their own methodology and explanatory strategies, but are embedded in a larger “philosophy.”

In this sense, evo-devo perspectives are *paradigms* of sorts, in which a characteristic set of *metaphors* play exemplary (in particular, heuristic and unificatory) roles, and possibly a negative role (demarcation from other approaches) as well. In Lewontin's (1996:1) words, "All sciences, but especially biology, have depended on dominant metaphors to inform their theoretical structures and to suggest directions in which the science can expand and connect with other domains of inquiry. Science cannot be conducted without metaphors. Yet, at the same time, these metaphors hold science in an eternal grip and prevent us from taking directions and solving problems that lie outside their scope." Metaphors also mediate between specific scientific cultures and the culture at large (see, e.g., Schlanger 1971; Haraway 1976; Tibon-Cornillot 1992).[7]

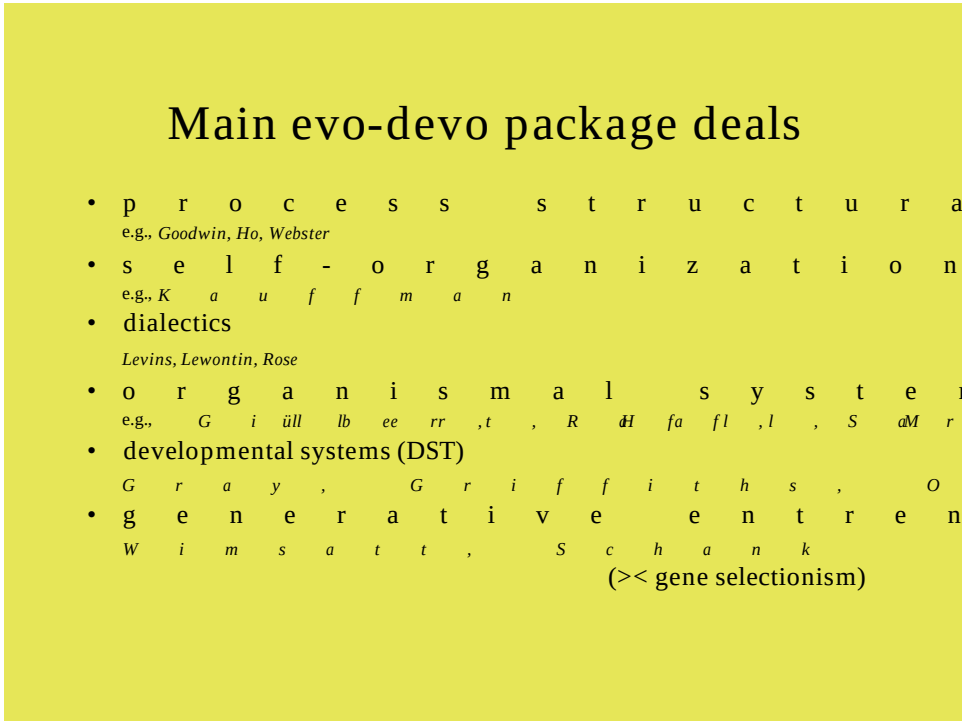


Table 1. Main evo-devo package deals, identified on the basis of both conceptual and sociological criteria. Gene selectionism (e.g., Cronin 1991; Williams 1992) is included as the anti-position which holds that "the details of the … developmental process, interesting as they may be, are irrelevant to evolutionary considerations" (Dawkins 1976). Philosophical and social-psychological ramifications of DST such as the extended replicator perspective (ERP) of Sterelny, Smith, and Dickison (1996) or Caporael's (1997) core configurations model are not discussed here.

Griesemer usefully distinguishes between theories, perspectives, and images. Following Levins (1968), he views theories as "collections of models and their robust consequences" that represent and interpret phenomena (Griesemer 2000: 350). Theoretical *perspectives* coordinate models and phenomena; such coordination is necessary because phenomena are complex, our scientific interests in them are heterogeneous, and the number of possible ways of representing them in models is (too) large. Adequate theorizing may require a *variety* of perspectives and models — a point worth keeping in mind in discussing what the "right" account of evo-devo is. Genetic determinism is an instance of a perspective. Theoretical perspectives are expressed in *images* that specify preferred lines of abstraction from phenomena of interest and prioritize principles in terms of which models may be constructed to represent phenomena. Weismannism has been a historically immensely useful image of the genetic-

determinist perspective, as was Watson's central dogma diagram in the second half of the 20th century. Many biologists today still think of the genetic program image as heuristically fruitful. The developmental systems perspective (DSP) replaces the image of genes as privileged molecules that control both development and their own evolutionary fate by an image that favors a “causal democracy” of many kinds of developmental resources other than genes, rejects information talk for privileging genes, and relocates replication from the genetic level to the level of entire developmental (i.e., organism-cum-environment) systems (Griesemer 2000: 350). Griesemer tries to distinguish between DSP and DST as an ensemble of theoretical representations and interpretations of phenomena also dealt with by other models such as those of gene selectionism. However, it is not clear to us whether advocates of the developmental systems approach, which draws on research in a wide range of areas from animal and human behavior to molecular biology, really aim to supplement their critique of genic selectionism with a positive research program (see, e.g., Gray 2000: 185; Oyama 2000). Propagating the correct *Weltanschauung* often seems more important here than caring for the nitty-gritty details involved in working out predictive models.

What is an image, specifically? Here the notion of a paradigm, or more specifically, that of an exemplar that guides and motivates researchers, still seems useful.[8] One function of exemplars is to make phenomena intelligible to students, researchers, and the public at large (that the genetic program image is catchy is plain enough). Images that display a *mechanism*, especially if they are visual, are particulary apt to engender intelligibility, as they "show *how possibly, how plausibly,* or *how actually* things work" (Machamer, Darden, and Craver 2000: 21). The intelligibility of an image must not be confounded with the correctness of an explanation: images often will convince us even if, as (shorthand for) explanations, they are incorrect. Intelligibility is probably "a product of the ontogenic and phylogenic development of human beings in a world such as ours" (p. 22). As such they may also evoke emotions, which in turn may act as positive or negative motivators. If you want to convince a geneticist of the plausibility of an epigenetic account of development, nice 3D reconstructions in motion may work wonders, whereas the best of arguments could fail.

Coming back to the general issue of evo-devo package deals, we must ask to what extent the close links that are often suggested between specific theoretical notions and specific metalevel views are really robust or even inevitable or rather the result of the contingencies of one’s scientific and philosophical education, or social background or standing. As a meta-discourse, the dialectical account often seems quite disconnected from the research practice of its advocates, to take this one example. Smith (1992) instantiates a general tendency to posit the existence of a neorationalist, “European view of metatheory” (p. 433) which is taken to be "more holistic and less empirical than its American counterpart” (p. 449). He associates this view with Riedl’s and Wagner’s systems-theoretical analyses as well as with Goodwin’s “process

structuralism." Although there is some truth in this view (Callebaut 1998), this picture is too undifferentiated. Riedl's evolutionary epistemology, for instance, is ultimately much closer to Humean empiricism (with its emphasis on regularity rather than causation as production) than the scientific-realist view that dominates current Anglo-American philosophy of biology. On the other hand, Hooker (1995: 227), Mahner and Bunge (1997: 294—299), and others have argued convincingly that there is no need to accept such a dichotomy as suggested by Smith. One can resituate neo-Darwinian processes within a complex systems framework without going to either empiricist or rationalist extremes, which is the approach taken here (cf. Robert 2002).[9]

Against the background of evo-devo package deals, the issue of the modesty or ambition of the various perspectives is not a tactical question ("Are we more likely to get our views accepted by suggesting that we contribute to the orthodoxy, or should we rather play the young Turks?"), let alone rhetorical flourish. Rather, at stake are the actors' deepest methodological, epistemological, and metaphysical convictions, their scientific ethos (contrast, for instance, the gene-selectionists George Williams's and Edward Wilson's austerity with the pluralist Gould's playfulness), and perhaps even their politics and ideology.[10] As scientific realists (philosophically speaking) we are tempted to add that one should also realize that in the absence of any direct access to the Truth, it is ultimately on the success or failure of scientific careers as proxies for Truth that bets are taken (David Hull). No wonder that debates will at times be harsh! Difficulties in communication between the contending parties stem in part from what sociologists and historians of science call the *boundary work* that accompanies scientific discipline building (see, e.g., Galison and Stump 1996). An important task incumbent on philosophers and historians of biology will be to probe how deeply entrenched the meta-commitments of the advocates of the various perspectives on evo-devo really are.

3. Reversing Foreground and Background: From Genetics to Epigenetics

Sansom (2002) diagnoses the exclusion of development from the study of evolution for most of the second half of the twentieth century as the result of a "misconstrual" of the role of genes in evolution: If the gene is taken as the atomic unit of evolutionary change, natural selection can be thought to "look through" the organism right to the genome, rendering the process of development epiphenomenal to the process of evolution. On this construal, the evolution of development of a full-fledged organism was but a ruse of natural selection to increase the fitness of individual genes. This view has many flaws — the "bean bag" assumption, the assumption that genes are self-replicating, etc. — which have been sufficiently exposed to dispense us from their elaborate discussion here (see, e.g., Lewontin 2000, the papers in sections A and B of Singh et al.

2001, or Robert 2002). For our purposes in this paper it will suffice to elaborate on the keywords *causation* (agency), *emergence*, and *pluralism* in the sense of a multilevel, hierarchical theory of natural selection, taking Gould's (2001) account as our point of departure.

(1) Causation

Replication must be relegated from the prominent role it plays in the gene-centric view of Williams, Dawkins et al. because it is not, and cannot be, the locus of agency. In Gould's (2001: 213) words, "units of selection must be actors within the guts of the mechanism, not items in the calculus of results."[11] Griesemer's replacement of replication by (re)production processes (see below) begins to pave the way for a full-fledged philosophical account of evolutionary-developmental processes as causal-mechanical processes, which can be genetic, epigenetic (Fig. 2), or caused by interactions with the environment. "Because … inherent physical properties, in their self-organizing capacities, but also conditioned by external parameters and extrinsic forces, can act as morphogenetic determinants, the dynamical, constraining, and environmental aspects of developmental causation can productively be analyzed in the framework of inherency and interaction, i.e., epigenesis" (Newman and Müller 2002). The philosophical view that naturally fits the causal-mechanistic approach of evo-devo is a variety of scientific realism that accounts for explanation in terms of mechanistic models, capacities, and major factors and relinquishes the covering-law approach (see, e.g., Bechtel and Richardson, 1993; Wimsatt, collected works; Machamer, Darden, and Craver, 2000; cf. Salmon 1984). This is not to say that functional and teleological explanation can be dispensed with at all levels (cf. Sober's [1983] "equilibrium explanations"). When, for instance, OSA interprets homologues as attractors of morphological design (see note 12), this clearly begs for an equilibrium explanation. But the hope is that they can be rephrased so as to fit the causal explanatory mold.

(2) Emergence

Gene-centrism counterfactually supposes that genes build organisms entirely in an additive fashion without nonlinear interactions among genes. However, the fact of emergence is undisputable. "This aspect of the question is empirical but also entirely settled (and never really controversial): organisms are replete with emergent properties; our sense of organismic functionality and intentionality arises from these emergent features" (Gould 2001: 213; cf. Schlanger 1971). Thus Dawkins' colorful metaphors of selfish genes and manipulated organisms "could not be more misleading because he has reversed nature's causality: organisms are active units of selection; genes, although lending a helpful hand as architects, remain stuck within." (pp. 213—214) (cf. Fig. 2). Hull's (1982, 1988) apt replacement of Dawkins' replicator-vehicle distinction by replicators and "interactors," respectively, fine-tunes Lewontin's (1970) formalization of evolution as "heritable variation in fitness," but needs to be complemented by an account of

what is *materially* transferred in evolution and development (Griesemer 2000 and forthcoming). Individuals need not *replicate themselves* to be units of selection; it suffices that they contribute to the next generation by hereditary passage and "magnify" their contributions relative to those of other individuals (Gould; cf. Lewontin 1996). Selection, then, occurs "when this magnification results *from the causal interaction of an evolutionary individual* (a unit of selection) *with the environment* in a matter that enhances the differential reproductive success of the individual." (Gould 2001: 216).

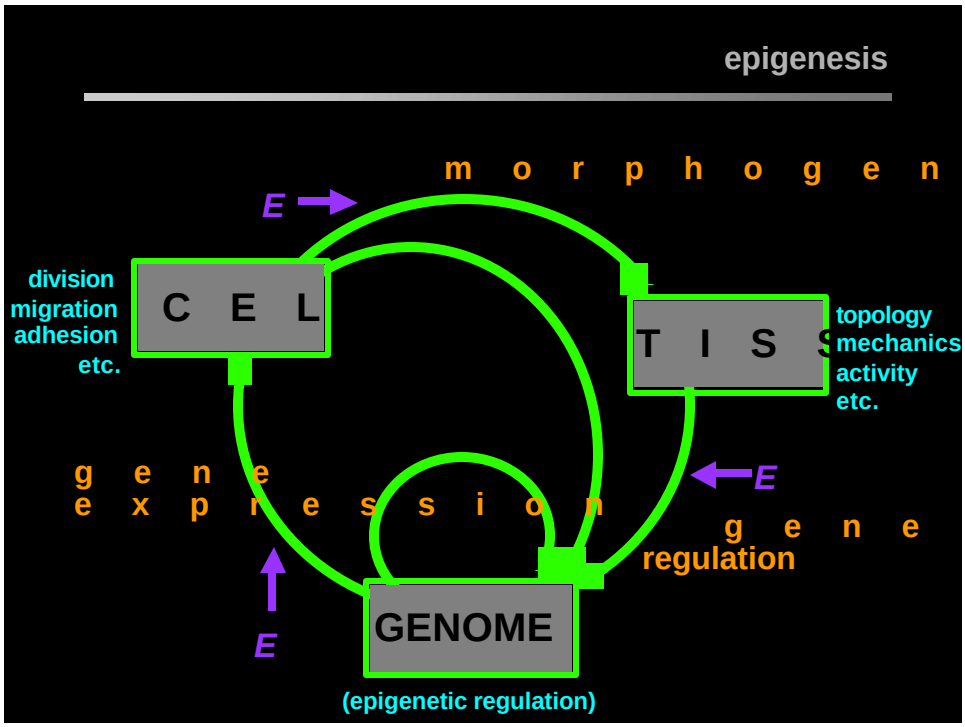


Fig. 2. Epigenesis (Müller).

(3) Levels pluralism

Group selection "has risen from the ashes to receive a vigorous rehearing" (Gould, ibid.; see most notably Sober and Wilson 1998; cf. Wimsatt 1980 and Sterelny and Griffiths 1999), resting on two proposals that Gould and others believe can serve as centerpieces for a general theory of macroevolution: "(1) the identification of evolutionary individuals as interactors, causal agents, and units of selection; and (2), the validation of a hierarchical theory of natural selection based upon the recognition that evolutionary individuals exist at several levels of organization, including genes, cell lineages, organisms, demes, species, and clades" (Gould 2001: 216).

Reclaiming the phenotype — understood as a multilevel, hierarchical system — as the central concern of biology, we must take issue with Smith and Sansom's (2001) claim that "Evolution has resulted in organisms that develop." Relocating the causal nexus in epigenetic processes, we want to propose instead that "Development has resulted in populations of organisms that evolve." Section 4 will be essentially an elaboration of this reversal of foreground and background.

4. The organismal systems approach (OSA) to evo-devo

The research strategy of evo-devo as the empirical and theoretical analysis of the causal connection between embryological/developmental and evolutionary processes may be viewed as dialectical. On one hand, evo-devo is interested in the factors that together explain the origination of ontogenetic systems and the mechanisms that account for their subsequent modification. On the other hand, it investigates the ways in which the properties of ontogenetic processes can influence the course of morphological evolution (cf. Raff 2000).

How can the organismal systems approach (OSA) contribute to the Developmental Synthesis? In this paper we will concentrate on the epigenetic views of Newman and Müller, leaving a treatment of and comparison with other work for another occasion. In our view, the most original contributions of this variety of OSA are plausible theoretical and where possible also empirical accounts of (i):the qualitative ("pre-Mendelian") *generation* of primordial organismal form and structure; (ii) evolutionary *innovation* — how are novel elements generated?; (iii) the variety of causal processes that together make for the *organization* of the integrated, adult phenotype; and (iv) *developmental constraints* — why are not all the design options of a phenotypic space realized? In this paper we can only discuss the first two issues; for a more complete survey, see Callebaut and Müller (2002).

(1) Qualitative ("pre-Mendelian") generation of primordial organismal form and structure *(Newman and Müller 2000, 2002;*

The validity of the genetic program image for the development and evolution of form in metazoan organisms may be challenged (cf. section 1; Newman 1994; Müller and Newman 1999, 2000). A new way of conceptualizing the causal relationship between genes and form can resolve some of the current debates in evolutionary biology, as well as apparent paradoxes in developmental biology, that have arisen with recent findings of extensive functional redundancy in embryonic systems. According to OSA, the correlation of an organism’s form with its genotype, rather than being a *defining condition* of morphological evolution, is a *highly derived property*. This implies that other, nongenetic causal determinants of biological morphogenesis have been active over the course of evolution.

Plasticity of form and developmental trajectory provide an entry in this novel perspective. Organisms including protists, fungi, plants, and animals such as arthropods and molluscs may exhibit radically different froms in different microenvironments or ecological settings. Thus *Candida albicans*, a fungal pathogen in humans, does not seem to have a “default morphologiy” (Magee 1997); rather, it is able to switch among forms ranging from single budding cells, to threadlike hyphae, to strings of yeast-like cells plus long separated filaments (“pseudohyphae”). In reptiles, incubation temperature determines sex in reptiles in a species-dependent fashion: high temperatures produce males in lizards and crocodiles, but females in chelonians. In mice the number of vertebrae can depend on the uterine environment: fertilized eggs of a strain with five lumbar vertebrae preferentially develop into embryos with six vertebrae when transferred into the uteri of a six vertebrae strain. Metamorphosis in, e.g., echinoderms, tunicates, arthropods, and amphibians, can be influenced by environmental change as well as intrinsic timing mechanisms (Gilbert et al. 1996). Even in vertebrates organism-environment ineractions can play a decisive role in morphological development, e.g., amphibian metamorphosis, which can be influenced by environmental change as well as intrinsic timing nechanisms.

Neo-Darwinian interpretations of these polymorphisms present them as specifically-evolved adaptations and therefore sophisticated products of evolution. The different phenotypes consistent with a given genotype are thus considered to be programmed subroutines that have evolved as a result of distinct sets of selective pressures at different life-history stages, manifestations of an evolutionary fine-tuned "reaction norm," or products of evolution for evolvabiity. However, according to OSA much morphological plasticity is held to reflect the influence of *external physico-chemical parameters on any material system* and is therefore primitive and inevitable rather than programmed (Table 2 and Fig. 4). Nonliving viscoelastic materials such as clay, rubber, lava, and jelly, for example, are subject (by virtue of inherent physical properties) to being molded, formed and deformed by the external physical environment (*soft matter*). Most living tissues are soft matter, and all of them are also *excitable media* — materials that respond in active and predictable ways to their physical environments. Some if not much of organismal plasticity results from such material properties.

Ancient organisms undoubtedly exhibited less genetic redundancy, metabolic integration and homeostasis than modern organisms, and were thus more subject to external molding forces. Hence it is likely that in earlier multicellular forms morphological determination based on an interplay of intrinsic physical properties and external conditions was even more prevalent than it is today. On the scenario that OSA proposes, then, morphological variation in response to the environment is a primitive, physically-based property, carried over to a limited extent in modern organisms from the inherent plasticity and responsiveness to the external physical environment of the viscoelastic cell aggregates that constitutes the first multicellular organisms.

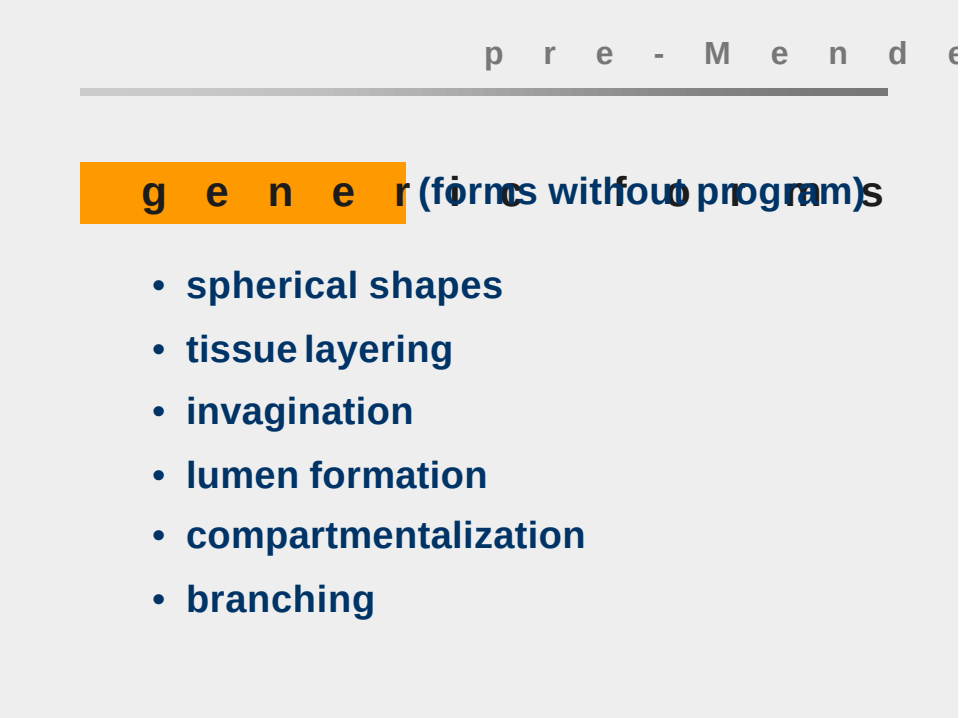


Table 2. Generic forms in the pre-Mendelian world
(Newman and Müller).

Mendelian and pre-Mendelian worlds (Table 3). — The correspondence of a given genotype to one morphological phenotype, as frequently seen in higher animals, will be exceptional, then. Such close mapping can result from an evolutionary scenario in which the developmental mechanism by which a phenotype is generated changes from being sensitive to external conditions to being independent of such conditions. If modern organisms are "Mendelian," in the sense that genotype and phenotype are inherited in close correlation, and that morphological change is most typically dependent on genetic change, then the OSA hypothesis can be encapsulated in the postulate that there was a "pre-Mendelian world" of polymorphic organisms at the earliest stages of metazoan evolution whose genotypes and morphological phenotypes were connected in only a loose fashion (Figs. 5 and 6). In this exploratory period of organismal evolution, the mapping of genotype to morphological phenotype would have been one-to-many, rather than one-to-one. With the subsequent evolution of *genetic redundancies* (e.g., A. Wagner 1996) and other mechanisms supporting reliability of developmental outcome, a closer linkage between genetic change and phenotypic change was established. In particular, with evolution under selective criteria favoring the maintenance of morphological phenotype in the face of environmental or metabolic variability, organisms would come to be characterized by a closer mapping of genotype to phenotype, giving rise to the familiar Mendelian world. But even as body plans and other major morphological features, such as the bauplan of the vertebrate limb, became locked in by the accumulation of reinforcing genetic circuitry, fine-tuning of details of organismal,

and particularly organ morphology continued (and continues) to occur through an interplay of genetic and nongenetic factors.

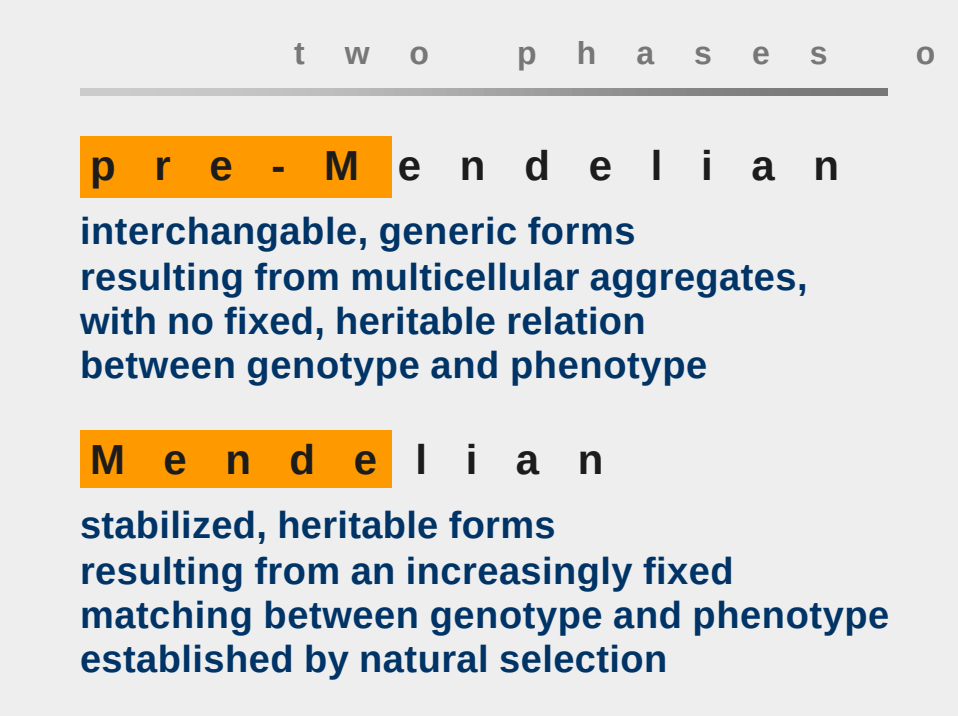


Table 3. Mendelian and pre-Mendelian worlds (Newman and Müller).

Example: adhesion (Fig. 3). — Many forms that arise during early stages of embryogenesis are either produced by mechanisms common to cell aggregates and nonliving materials (generic mechanisms), or resemble the outcome of such generic mechanisms. Physical attributes and behaviors of tissue masses and the forms that would be expected to arise from these inherent properties include diffusion and the formation of gradients, differential adhesion and compartment formation, and excitability and segmentation. Among the earliest examples of biochemical differentiation to have become established in the metazoan world was differential expression of adhesivity. Adhesion, being an evolutionarxy novelty in the earliest multicellular forms, would have been tolerated by the constituent cells over a wide range of expression levels. Even without additional functional differentiation, differential adhesion would have generated a panoply of morphologically distinct forms — multilayered, hollow, segmented, separately and in combination. This early form of differentiation would have led readily to the establishment of novel organismal form with the capacity to populate correspondingly new ecological niches.

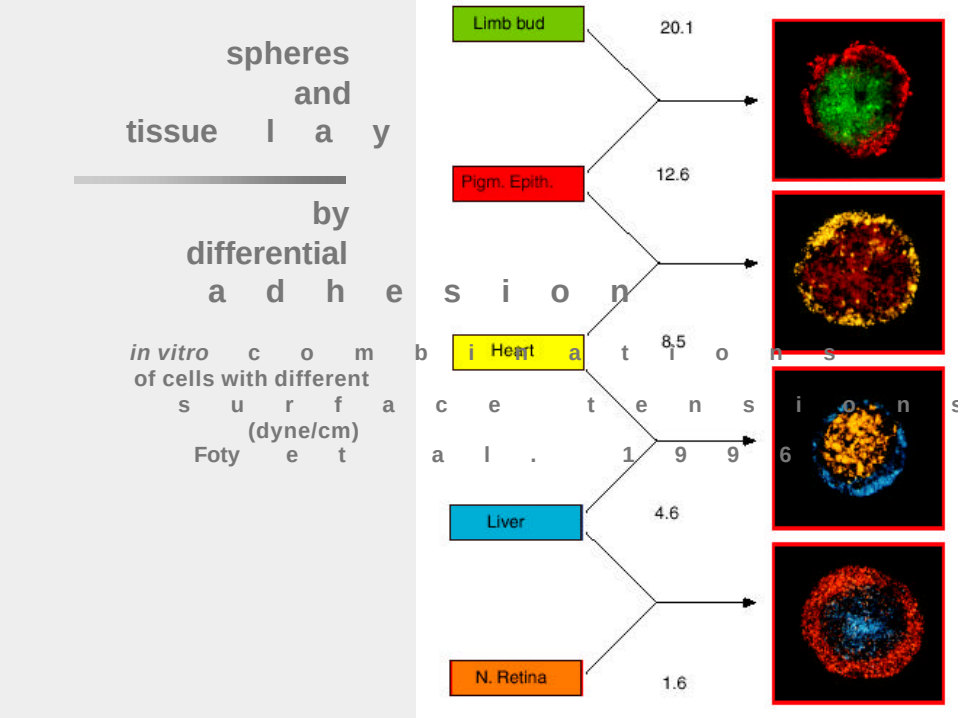


Fig. 3. Spheres and tissue layering by differential adhesion (Newman and Müller).

The developmental program: reality or appearance? — Once morphological characters emerged through the interplay of epigenetic and genetic factors, they served as templates for the accumulation, by natural selection, of stabilizing, reinforcing and overdetermining regulatory mechanisms. The processes by which morphological characters were determined were therefore different at different phases of evolution, with genetic integration taking on a more prominent role after a morphological feature had been established. As a result, the action of the originating epigenetic factors may be obscured or even superseded in a modern organism, with the succession of linked gene activities involved in development taking on the appearance (though not the reality) of the developmental program.

Meta-evolution. — Darwin recognized that biological forms evolve, but neither he nor his successors considered the possibility that the nature of the process that generated these forms could itself evolve in a systematic way. In Newman and Müller's view these mechanisms have evolved from a condition of more to less dependence on inherent material properties, and from less to more dependence on hierarchical genetic integration. Forms have evolved, and so have the ways they are generated, i.e., developmental mechanisms. "The failure of the neo-Darwinian synthesis to take account of such evolving generative mechanisms led to a situation in which, while it was acknowledged that not all genetic change had phenotypic consequences, all phenotypic change was seen to be due to genetic change" (Newman and Müller 2002).

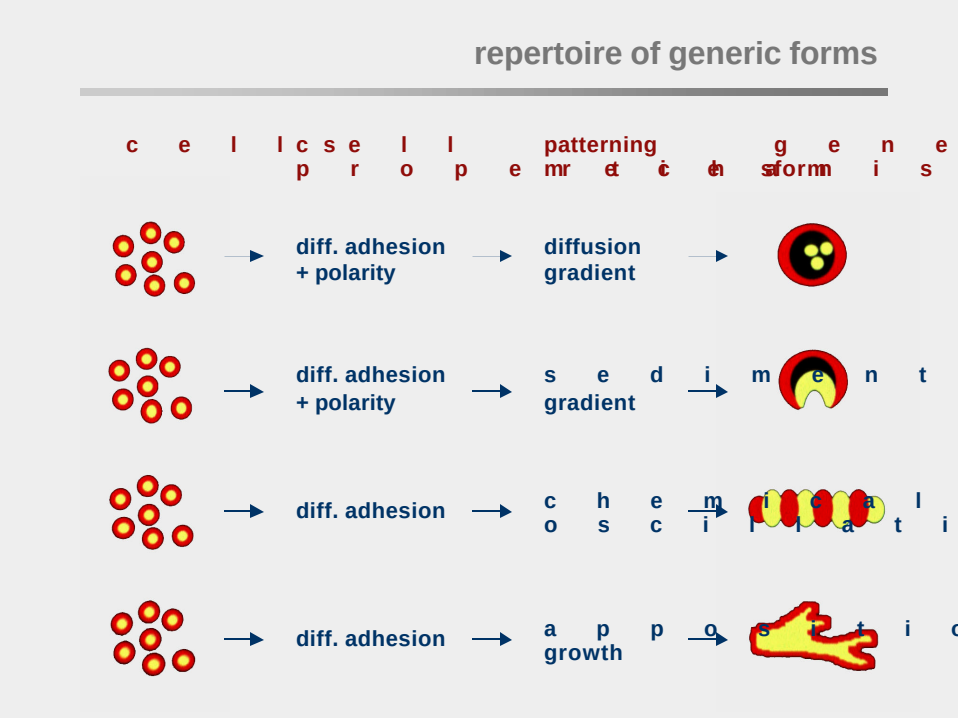


Fig. 4. Repertoire of generic forms (Newman and Müller) In principle, virtually all the features seen in early development of modern metazoan organisms can be attributed to the composition of one or more of the pattern forming mechanisms with differential adhesion (Newman 1994). The combined effects of the various physical properties that were generic to the earliest multicellular aggregates considered as chemically excitable, viscoelastic soft matter, ensured the production of a profusion of forms. This pre-Mendelian world of morphological prototypes provided the raw material for natural selection and was thereby converted in to genetically routinzed body plans.

Predictability. — If the organization of organisms is (in an evolutionary sense) a largely predictable consequence of the inherent material properties of their constituent tissues, then it is inaccurate to see genetic change as the driving force (as opposed to one necessary component) of hereditary morphological change. Similarly, if organismal forms were originally brought about by interactions of cell masses with one another and their microenvironments based on their inherent properties (Fig. 4), and only later integrated into developmental repertoires by stabilizing and canalizing genetic evolution, then the causal basis of developmental morphogenesis cannot simply be differential gene expression (cf. the section on innovation below).

Primacy of epigenetics. — By considering the emergence and transformation of developmental mechanisms as an evolutionary problem in its

own right, OSA arrives at the view that epigenetic mechanisms, rather than genetic changes, are the major sources of morphological innovation in evolution. Note that here "epigenetic" refers to the context-dependence of developmental mechanisms, not to DNA-associated mechanisms of inheritance, such as methylation and chromatin assembly" (see Müller and Olsson 2002 for a review).

Inherency. — While the watchword of neo-Darwinism is contingency, OSA emphasizes inherency. "Something is contingent if its occurrence depends on the presence of unusual (we might say aberrant) conditions that occur accidently, conditions that involve a large component of chance," while "something is inherent either if it will always happen (e.g., entropy) or if the potentiality for it always exists and actuality can only be obstructed" (Eckstein 1980, quoted in Newman and Müller 2002).

Implications for expected tempo and mode of morphological evolution. — Generic forms, based as they are on inherent properties of tissue masses, would have been relatively straightforward to generate, but also delimited in their variety (not every form can be achieved using the described processes). Newman and Müller's view suggests a natural interpretation of the burst of morphological diversification recorded in the early Cambrian fossil record — including the capacity for a rapid elaboration (on the geological time scale) of virtually all the modern body plans. Even the Cambrian forms that failed to contribute to modern bodyplans have the appearance of being constructed of different combinations of the standard morphological elements (Conway Morris 1989; Gould 1989). The OSA framework also suggests prior steps in the Precambrian era that possibly laid the basis for this "Cambrian explosion." The first morphologically complex multicellular organisms, represented by the Vendian fossil deposits (dating from as early as 700 million years ago), appear to have been flat, often segmented, but apparently solid-bodied creatures. It is thought to have taken up to100 million years (maybe less) after the appearance of ther Vendian fauna for organisms to develop distinct body cavities. Once these triploblastic forms arose, all the modern body plans burst onto the scene in short order. Thus the advent *of polarized cells* provided a plausible physical basis for the Precambrian origin of triploblasty. Whether cell polarity arose before or after any of the evolutionary events that led to multicellularity lumen or cavity formation would have been an inevitable physical consequence of the conjunction of these two properties (Newman 1994).

(2) Evolutionary innovation

The evolution of phenotypic characters proceeds by a two-stage process, consisting of the spontaneous generation of heritably phenotypic differences and the fixation of these changes in a population. This applies to any form of phenotypic evolution, viz., adaptation, innovation, and speciation, A distinction between innovation and adaptation implies that innovation represents a specific class of phenotypic change which is different from adaptive modification. This

applies to the origin of new body parts (entitities, units, or elements), such as feathers, or eyes, or limbs (*evolutionary novelties* — Table 4) as well as to major organizational transitions such as the origin of multicellular organisms. Innovations that have a major impact on adaptive radiation are called *key innovations*. The prediction is that specific innovations, whether based on novelty characters or physiological or functional innovations, open up possibilities for the exploitation of new energy sources and permit new adaptive radiation of the innovation-bearing group. The concept of key innovation thus provides a connection between innovations in structurally evolving organisms and the environment (eco-evo-devo!). Arguments in favor of the distinctness of innovations have been made on two grounds: (i) the origin of novelty may include *different mechanisms* than the mutations underlying variation and adaptation, and (ii) certain phenotypic changes may have more important and *long-lasting consequences* for the dynamics of evolution.

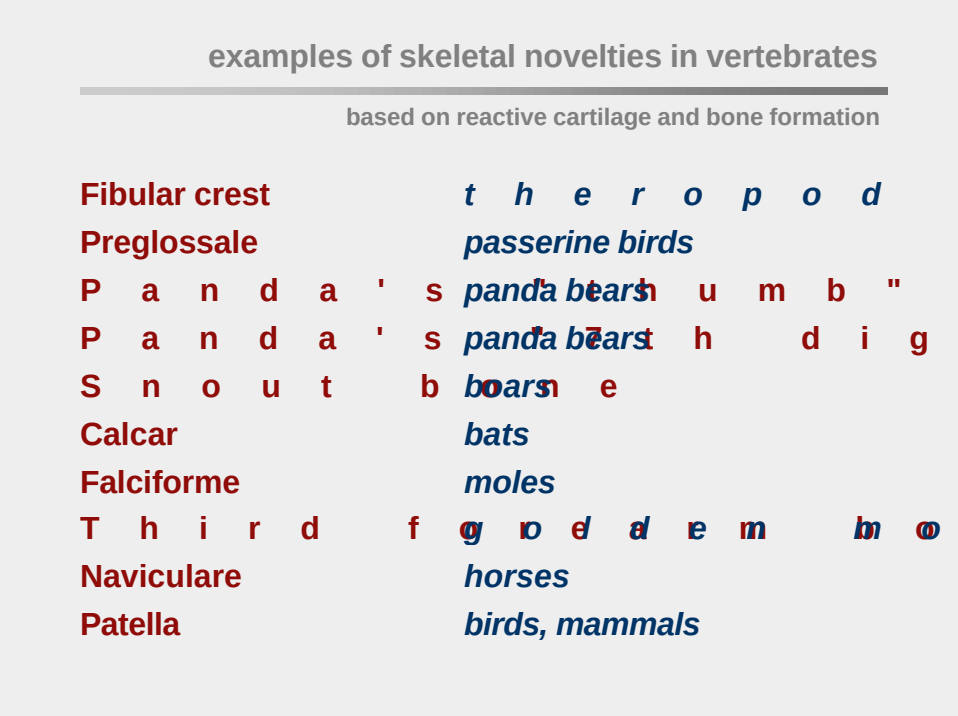


Table 4. Skeletal novelties in vertebrates (Müller).

Morphological novelty. — Several definitions of phenotypic novelty have been proposed, but in order to be sensible such a definition must be firmly rooted in a character concept that is adequate for the respective levels of organization. At the morphological level the most useful definition is based on the homology concept: a morphological novelty is a new constructional element in a body plan that neither has a homologous counterpart in the ancestral species

nor in the same organism (serial homologue) (Müller and Wagner 1991).[12] This excludes characters that lie within the normal range of variation, or deviate only quantitatively from the ancestral morphological condition. But it includes those cases in which a new homologue has arisen through individualization of a preexisting serial element. Novelty always represents a *qualitative* departure from the ancestral condition, not merely a quantitative one (Müller 1990). Examples of novelties that satisfy this definition exist in all tissues and organ systems of plants and animals.

Innovations pose special evolutionary problems. — The concept of innovation makes sense only if it refers to a set of evolutionary processes that raise specific and distinct research questions. Four such questions can be identified.

(i) Levels of selection: One class of major innovations consists of the integration of smaller replicative units units into a higher level replicator. Examples are the origin of the eukaryote cell from symbiosis with bacteria, the assocation of cells resulting in multicellular organisms, as well as the origin of colonies and eusocial communities (Buss 1987; Maynard Smith and Szathmáry 1995). All these transitions involve cooperation among replicative units (cells or individuals) to forn higher-level units which sacrifice the reproductive success of the lower-level units. Special conditions need to be fulfilled in order to overcome the competitions among the lower-level units and allow the origin of the higher-level ones.

(ii) Origination: Origination refers to the causality of the generative mechanisms that underlie the origin of new morphological characters (Müller and Newman 2002). The origin of new body parts or entire new body plans is often difficult to explain because of the sheer *phenotypic distance* between the ancestral and the derived phenotype. Some of these problems may be solved by the discovery *of transitional forms*, as in the transition from the primary jaw joint of reptiles to the secondary jaw joint of mammals. Other examples have mechanistic implications, because the transitions often require developmental modifications that are not within the mutational reach of the ancestral character state. An example is the origin of feathers. In such cases natural selection alone is only of limited explanatory value as the real problem consists of understanding the mechanisms for the origin of the new phenotypic state. It is thought that many innovations involve a breaking up of developmental or functional constraints that prevailed in the ancestral lineage. Whether this is indeed the case is an unresolved empirical question (e.g., Eberhard 2001; Wagner and Müller 2002).

(iii) Functionality: New body parts and characters are often associated with radically new functions not present in the ancestral lineage, as in the case of insect wings. It is tempting to assume that the new function is to some extent responsible for the origin of the novelty. The problem, though, is that the derived function often requires a highly developed form of the new organ (e.g., the insect wing). The solution is supposed to lie in a transfer of function: the new structure would initially serve a different function and becomes only secondarily co-opted into the derived function.

(iv) Integration: The functional interdependency of morphological characters leads to various kinds of connections and couplings among the characters that will influence their evolutionary fate. These couplings often have negative effects on the evolvability of characters. Here the problem is how evolutionary innovations are accommodated into the preexisting, tightly coupled system of a body plan. *Homology* arises when a new element is locked into the constructional body plan and is maintained in at least one derived species. Integration is likely to take place through different mechanisms, acting among and between different levels of organization — genetic, developmental, phenotypic, and functional. Not all integration necessarily corresponds to early genetic fixation. Many phenotypic characters can be experimentally suppressed by changing the epigenetic conditions of their formation.

The existence problem. — Mechanistically, morphological novelties can be based on developmental innovations at the molecular or cellular level, or on new developmental modes and interactions. They can equally arise from the redeployment of any of these components at a new location in the embryo, through subdivision or combinationnof earlier structures, or through developmental individualization of serial structures. These changes of developmental mechanisms should not be confounded with the ultimate evolutionary factors that elicit novelty by acting on developmental systems. Novelty, as a deviation from quantitative variation, is not easily explained by the conventional mechanisms of evolution. It is difficult to implicate selection as the direct cause of novelty, because selection can only act on what exists already.

If the tape were played twice… — In this context, Fontana and Buss's (1994a, 1994b) modeling of an abstract chemistry implemented in a λ-calculus-based modeling platform is highly relevant. In their model world the following features are generic, and hence would be expected to reappear if the "tape" of evolution were run twice: (i) hypercycles of self-reproducing objects arise; (ii) if self-replication is inhibited, self-maintaining organizations arise; and (iii) self-maintaining organizations, once established, can combine into higher-order self-maintaining organizations. Darwinian selection presupposes the existence of self-reproducing entities. But self-maintaining organizations can arise in the absence of self-reproducing entitities. “Self-reproduction and self-maintenance are shared features of all extant organisms, barring viruses. It is not surprising, then, that there has been littlle attention paid to the generation of one feature independently of the other. While selection was surely ongoing when transitions in organizational grade occurred in the history of life, our model universe provides us the unique opportunity to ask whether selection played a necessary role" (Fontana and Buss 1994a: 761). Fontana and Buss's findings clearly indicate that it need not. Moreover, "separating the problem of the emergence of self-maintenance from the problem of self-reproduction leads to the realization that there exist routes to the generation of biological order other than that of natural selection…. Indeed, this is apparent upon inspection of the formal structure of the theory, Neo-Darwinism is about the dynamics of alleles within populations,

as determined by mutation, selection, and drift, A theory based on the dynamics of alleles, individuals, and populations must necessarily assume the prior existence of these entitites. Selection cannot set in until there are entitities to select. Our exploration of an abstract chemistry not only provides a route to generate such entities but illustrates that different organization grades can arise in the absence of selection. This raises the problem of determining which features of biological organization are attributable to the emergence of the organization and which features are attributable to its subsequent modification by selection. At issue is the primacy of natural selection in shaping the major features of biological organization" (ibid.).

Newman and Müller (2002), while not disputing that the primary causes of evolution are Darwinian, insist that "at the developmental level genomic changes will essentially influence quantitative developmental parameters and will not cause qualitative novelty per se. … Novelty arises at the transgression of threshold points immanent to developmental systems, where sequences of developmental interactions are disrupted or new interactions become established, and the resulting structure will depend on the reaction norms of the system at that point." Physical principles, including biomechanical factors, are active in secondary developmental fields. "In such limited domains flexibility and conditionality of morphological outcomes are less likely to undermine overall organismal integration than similar lack of fixity at the body plan level. … Much as alloys and composite polymeric materials exhibit properties not readily predictable from the physics of simple liquids and solids, so will the outcomes of physical processes in secondary developmental fields be less "generic" and more idiosyncratic than those of the liquid-like cell agregates that existed at earlier stages of metazoan evolution. Thus, while tha basic body plans of metazoa, having been established in the earliest period of multicellularity, may bear the stereotypical stamp of physical molding forces acting on soft, excitable materials, later evolving organs and appendages will exhibit more particularitires. This is somewhat paradoxical since, in general, body plan organization wil have become more genetically consolidated and overdetermined with time, while organs and appendages, being evolutionarily "younger," may actually retain a greater amount of physically-based plasticity than the same organism's general body plan" (ibid.)

Three scenarios for the origin of phenotypic novelties. — Müller (2002) discusses three kinds of evolutionary mechanisms through which phenotypic novelties may arise. *(i) Rare mutations that generate immediate structural effects:* This scenario is based on the notion that genetic change provides the raw material not only for gradual variation but also for kernels of new structural elements. This is unlikely a widespread mode of phenotypic character innovation, but could underlie such cases as the origin of feathers, whichi seem to be based on a new macroscopic property of scales introduced by a new keratin resulting from gene duplication and deletion effects. *Symbiosis:* This scenario assumes the successful combination of genetic material from distantly related organisms. The occurrence of symbiosis is recognized as a source of

innovation in the evolution of bacteria, fungi, algae, and eukaryotic cells, but also in certain evolutionary instances of more complex organisms, although its importance seems to have receded in advanced forms of plants and animals. Symbiosis and other horizontal transfer might not only lead to the combination of pieces of DNA from different sources but could also include the transmission of entire genetic/developmental modules between species. More common seems (iii) the scenario that proposes that novelties are largely epigenetic in origin, both in pre-Mendelian and Mendelian stages of evolution. Selection acting on other features than the novel character itself, such as organismal proportion, function, or behavior, is thought to elicit epigenetic by-products that arise from generic properties of the modified developmental systems — *the side-effect hypothesis* (Müller 1990). An example are novel skeletal elements that form at new locations based on changes of cell number, blastema size, and mechanical load that accompany proportional modifications of a body part (Table 4).

In all three modes, the incipient novel structure is nonadaptive in origin. Mechanisms that are able to overcome existing constraints must be postulated, and genetic fixation and developmental routinization of a novelty may rise as secondary consequences through natural selection.

5. Epistemological and Pragmatic Aspects of the Developmental Synthesis

Will developmental biology "only" (re)supplement evolutionary biology, or could the Developmental Synthesis eventually prompt a fundamental theoretical rethinking of evolution itself (cf. Depew and Weber 1995)? The only honest answer is of course that it is too early to tell. Scenarios in terms of "modesty" versus "ambition" have been suggested. Before entering a discussion of some of the more obvious epistemological aspects of evo-devo such as tits potential to contribute to the further unification of biological theory, a caveat seems in order. The task the proponents of the Developmental Synthesis face may be so formidable that even achieving more modest aims may turn out Herculean. As so often, a historical perspective is useful here. Amundson (1994: 576) reminds us that "evolutionary biology was built on a huge black box — Darwin could never have written the *Origin of Species* if he had not wisely bracketed the mechanism of inheritance." One of the great advantages of Mendelian genetics in the early decades of the twentieth century, it is often thought, "was that it bypassed the uncharted swamp of development" (Hull 1998: 89). But today the situation looks radically different: "Pre-Synthesis Darwinians at least realized the need for a theory of inheritance, although they doubted that Mendelism was that theory. Most post-Synthesis neo-Darwinians do not require developmental biological contributions to evolution theory. Developmentalists may or may not be able to demonstrate that a knowledge of the processes of ontogenetic development is essential for the explanation of evolutionary phenomena" (Amundson 1994: 576). Provided they can demonstrate this, and offer well-founded

developmental/evolutionary explanations, the result will be “a dramatic synthesis of divergent explanatory and theoretical traditions,” Amundson concluded.

What kind of unification can evo-devo reasonably be expected to accomplish, or at least contribute to? In one mood, Kauffman (1993: 22—23) envisages a synthesis of evolutionary biology and developmental biology that on one possible reading would be based on an *identity of generative mechanisms*: "The task of enlarging evolutionary theory would be far more complete … if we could show that fundamental aspects of evolution and ontogeny had origins in some measure reflecting self-organizing properties of the underlying systems. The present paradigm is correct in its emphasis on the richness of historical accident, the fact of drift, the many roles of selection, and the uses of design principles in attempts to characterize the possible goals of selection.… the task must be to include self-organizing properties in a broadened framework, asking what the effects of selection and drift will be when operating on systems which have their own rich and robust self-ordered properties." Kauffman's vision provides one — as far as we are concerned, attractive — interpretation of what the long-term unifying function of evo-devo might be. At present, the actual and conceivable interrelations between the dominant neo-Darwinian, selectionist paradigm and the paradigm of self-organization are still quite unclear (Table 5).

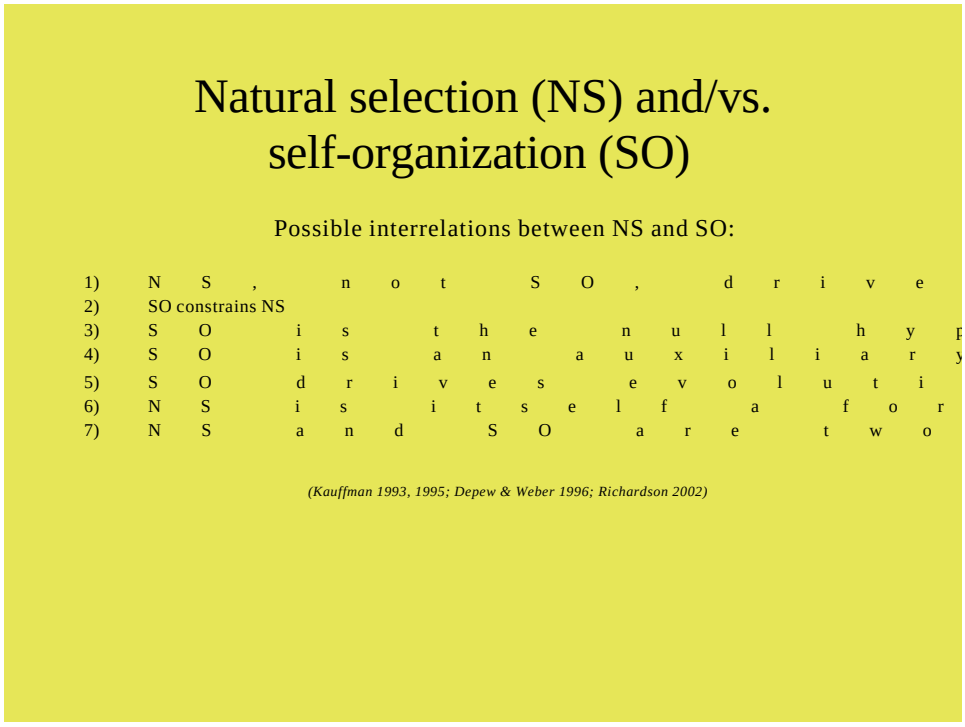


Table 5. Natural selection and/vs. self-organization,

Coming back to earth, we think it is fair to say that the contribution to a unified theoretical biology that most workers in the field *currently* envisage

(e.g., Wagner, Chiu, and Laubichler 2000) is much more modest. Rather than some grand unification scheme, what they have in mind can maybe best be rendered in terms of what Darden and Maull (1977) called an "interfield." On their analysis, a scientic field is an area of science consisting of a central *problem*, a *domain* consisting of items taken to be *facts* related to that problem, *general explanatory factors and goals* providing expectations as to how the problem is to be solved, *techniques and methods*, and sometimes (but not always) *concepts, laws and theories* which are related to the problem and which attempt to realize the explanatory goals (see also Darden 2002). If developmental biology and evolutionary biology — or more correctly, a number of their various subdiscipines which are relevant to evo-devo [13] — are regarded as fields, evo-devo might be regarded as an "interfield" that borrows resources from one field (say, a developmental analyses of homology) to solve a problem in another field (in our example, the evolution of homology).

Most historians and at least some philosophers of biology seem to agree that evolutionary biology is not a unified science, and that the Evolutionary Synthesis was not a conceptual/theoretical synthesis so much as an institutional synthesis (see, e.g., Smocovitis 1996; Burian 19 ##). Moreover, the ideal of a unity of science as envisaged by the logical empiricists and epitomized in Schaffner's account of reduction/replacement (e.g., Schaffner 1993) is no longer taken for granted, to put it mildly (see, e.g., Galison and Stump 1996). At least in biology, reduction does not work in practice; physicalist reduction, viz., the reduction of all the theories of complex objects to physics, is humanly impossible due to our bounded rationality (the physical correlate of a higher level property or kind is typically massively disjunctive, making it vanishingly unlikely that the properties or kinds of higher levels will enter into the kinds of universal laws characteristic of physics or chemistry). Further obstacles to unification are related to the data-driven nature of much contemporary research and, related to that, to what Suppes has called the reign of theory pluralism: "since World War II the engines of empiricism have vastly outrun the horse-drawn carriages of theory" (Suppes 1979).

If the postmodernist fashion to celebrate the end of the unity (singular) of science (singular) was all there was to it, the rhetoric of evo-devo enthusiasts calling for a Developmental Synthesis would be shallow indeed. But we take it that the one-sided ideology of unification dear to the (later) positivists has only be replaced by an equally misplaced exclusive focus on the factors in scientific practice that tend to diversity and separate scientific discourses. A more balanced view should take into account both the unifying and disunifying tendencies that have characterized most if not all sciences (and other social systems for that matter) from the very beginning.

We want to apply this view to Hacking's essayistic, yet deep analysis of "the disunities of the sciences" (1996). Hacking claims that throughout most

of our century, "regimes and practices of experimentation and instrumentation have been more powerful as a source of unity among diverse sciences than have grand unified theories" (Hacking 1996: 69). Instruments (Clarke and Fujimura 1992) are speedily transformed from one discipline to another, not according to theoretical principles but in order to interface with phenomena. As an example, Hacking mentions the tunneling electron microscope: at first thought suitable only for metallurgy, it has expanded into cell biology “in ways not all that well thought-out, and sometimes by accident.” The application of GIS technology or 3D imaging techniques to developmental processes provide other obvious examples. Hacking proposes a literally "instrumentalist" thesis: "it is not high-level theory that has stopped the innumerable branches of science from flying off in all directions, but the pervasiveness of a widely shared family of experimental practices and experimentation” (ibid.) For Hacking, mathematical tools have played a similar role as *pragmatic unifiers* since the day of Descartes, Newton, and Leibniz.

Although useful as a corrective to a misconception of theoretical science that is still widespread among philosophers and scientists alike, we believe that Hacking, too, misses an important part of the picture. We want to contend that material and virtual techniques and instruments not only have a potential to unify the thinking of researchers in different fields but can also *alienate* workers within and among fields. The difficulties of artificial life researchers to have not only their results but their whole way of proceeding accepted by mainstream biologists is one example out of many. Likewise, mathematics — and mathematical modeling in particular — is to be regarded not only as a unifier but as a potential disunifier as well. For modeling, as Israel (1996) succinctly put it, amounts to no less or more than the abandonment of the old Newtonian dream of reaching a unified picture of nature, since a single model may represent different fragments of reality, and the same fragment of reality can be represented by different models. This does *not* contradict our earlier endorsement of Griesemer's characterization of theories as "collections of models and their robust consequences” to the extent that much contemporary science, including biology, is often quite deficitary in terms of theory. What makes many a scientist tick is often the appeal of a single model as "image" (Griesemer), however ill-conceived. Moreover, as we know from many scientific controversies, methodological caveats are all to easily forgotten.

Laws and natural kinds. — Another topic for philosophical investigation that could deepen and enrich evo-devo's self-understanding is the vexing role of laws in biology and, intimately related to that, the function of natural kinds in biological modeling and theorizing (Griffiths 1996; Wagner 1996). One extreme position would want to dispense with biological laws altogether on the ground that even in the practice of physics they play negligible roles only (cf. Giere 1999). The other extreme position, represented by certain process structuralists,

is that developmental biology will deliver the goods. Thus Eble and Goodwin (forthcoming) write that "the successes of evolutionary developmental biology suggest that the comparison of historical and developmental kinds in developmental morphospace may soon generate more immediate insight into the nature of evolution than the comparison of historical and adaptive kinds in fitness landscapes." OSA's view of inherency (cf. section 4) clearly situates it toward the latter end of the spectrum (Callebaut and Müller 2002). Here too, a pluralism of approaches seems desirable if one accepts that there are different ways of partitioning the biological world, that different processes may relate to different partitionings, and that the different kinds of entities so defined may play roles in distinct theories of natural stability and change (Eble and Goodwin). In Callebaut and Müller (2002), we explore the connections between laws, homologues as natural kinds, and causal-mechanistic explanation in evo-devo in some detail.

Notes

[1] Nanney and Wilson (2001: 735—736) write that philosophy of biology has broadened its horizon considerably over the last ten years. They correctly point out that while issues at the core of evolutionary biology remain focal, interests both within and beyond evolutionary biology have diversified significantly. Yet the almost obsessive concentration of current Anglo-American philosophy of biology (and to a lesser extent, history of biology) on *Darwinian* issues in a broader sense, to the detriment of other subjects and intellectual currents such as the rich Continental-European traditions in theoretical biology, remains a matter of concern.

[2] In developmental biology this notion has gained seeming confirmation in findings that successive developmental steps are typically triggered by episodes of new gene expression and that experimental alteration of gene expression frequently leads to changed developmental outcome. In evolutionary biology the tenet that genes determine form is essentially equivalent to the reigning neo-Darwinian paradigm: (i) evolution is the hereditary transmission of phenotypic change; (ii) genes are the medium of heredity; (iii) the sum of selected genes therefore specifies and determines the phenotypic differences between organisms.

[3] Thus one can agree that there is no a priori or a posteriori justification for privileging genes over other developmental resources (Griffiths and Gray 1984: 283) without simultaneously endorsing the (strong) "parity thesis" promoted by developmental systems theorists, according to which other developmental resources can take over whatever genes can do.

[4] For Gerhard and Kirschner (1997), evolvability is the capacity of a process to generate nonlethal functional variation on which selection can act. In our own epigenetic framework, evolvability is interpreted in an entirely different fashion. It represents the *continued efficacacy of epigenetic processes in a lineage* — some of them quite ancient, others of more recent origin — and as such is tied to primitive morphogenetic plasticity. Genetic evolution will tend to suppress such evolvability and buffer the development of form (Newman and Müller 2000: 306).

[5] We agree with Wagner, Chiu, and Laublicher (2000: 821) that development "can be seen as another set of biological characters that evolve," but our emphasis on the primacy of epigenetic mechanisms suggests that the evolution of development cannot be adequately captured within the reigning, gene-centric neo-Darwinian paradigm and should therefore be at the heart of the evo-devo enterprise.

[6] As Robert, Hall, and Olson (2001: 957) note, "the aims of evo-devo are not carved in stone," which is what one would naturally expect on an evolutionary account of science a la Hull (1988).

Yet the lists of the aims of evo-devo of Hall (2000) and Wagner, Chiu, and Laubichler (2000) map almost one-to-one to each other.

[7] "The reason why competition, selfish genes, struggle, adaptation, climbing peaks in fitness landscapes, doing better and making progress, are so importaqnt as metaphors in neo-Darwinism is because they make sense of evolution in terms that are familiar to us from our social experience in our culture" (Goodwin 1994: #).

[8] Given the inflationary use of the term “paradigm” that followed its popularization by Thomas Kuhn, most philosophers of science has become wary of the term. The feature we have in mind was better captured in Kuhn’s rendering of the so-called “disciplinary matrix.” As a kind of scientific *Weltanschauungen*, disciplinary matrices are acquired largely implicitly during scientific education, in which the learning of “exemplars” — archetypical applications of symbolic generalizations or theories to phenomena — is of paramount importance. Commonness of vocabulary and “symbolic generalizations” notwithstanding, scientific communities with different exemplars will hold different theories, and hence will "view the world differently." Still according to Kuhn, depending on one’s exemplars one will also tend to ask different questions and hold different values. (For a critical assessment, see Suppe 1977: 138—151.) At the level of *Weltanschauungen* biological discourse is heavily imbued with metaphors. To the extent that they also function in the society at large (cf. above), Kuhn’s internalist picture of scientific communities as esoteric cultures must be corrected:

[9] Hooker (1994) has argued for this position in painstaking detail in the case of Piaget’s biology and genetic epistemology. In a similar vein, Amundson (1983) has shown for the debate between behaviorists and cognitivists in psychology that paradigmatic “package deals” are not necessarily as monolithic as they are often presented.

[10] Cf. Maynard Smith’s (1998) concluding chapter 5, “Reductionists to the Right, Holists to the Left,” whose moral is that “it pays to be eclectic in our choice of theories”, being “reductionist in one context and holist in another” (p. 45).

[11] Gould omits to credit Wimsatt’s [1980] analysis of the explanatory impotence of “genetic bookkeeping” accounts.

[12] Homology, in its most evolved form, is characterized by an increasing independence from the underlying developmental, molecular, and genetic processes that led to the first appearance and subsequent fixation of basic individual homologues (*autonomization* — Müller and Newman 1999). The same phenotypic endpoint can be reached via different developmental pathways, and these pathways have changed importantly in the case of structures that are clearly homologous (Hall 1995). Autonomization of homologues is a consequence of a decoupling between genetic and morphological evolution, "Homologues, the design units of the phenotype, transcend their underlying molecular, epigenetic, and genetic constituents and assume an independent, organizational role in morphological evolution. With their integration into the bauplan of a phylogenetic lineage, homologues take on constructional identity and come to act as accretion points of further structural organization. They can be understood as 'attractors' of morphological design (Striedter 1998; Müller 1999), around which more design is added, and will be conserved even in the face of changing adaptive conditions. Therefore, at this autonomized stage, homologues are more influential for the further path of morphological evolution than the primary generic conditions underlying their origin and the biochemical circuitry that controls their developmental formation" (Müller 2002).

[13] We agree with Gilbert (2001b) that "not all parts of developmental biology and not all parts of evolutionary biology are involved in these new unions," although we do not share his exclusive focus on developmental genetics and population genetics. The situation is actually more complicated since "paleontology, morphometiics, QTL mapping, ecology, life history strategy research, and functional morphology" — and, we would add, biophysics — are also involved. If

evo-devo is taken to include ecological considerations, thist list must be even further expanded (Gilbert 2001a).

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[5] We agree with Wagner, Chiu, and Laublicher (2000: 821) that development "can be seen as another set of biological characters that evolve," but our emphasis on the primacy of epigenetic mechanisms suggests that the evolution of development cannot be adequately captured within the reigning, gene-centric neo-Darwinian paradigm and should therefore be at the heart of the evo-devo enterprise.

[6] As Robert, Hall, and Olson (2001: 957) note, "the aims of evo-devo are not carved in stone," which is what one would naturally expect on an evolutionary account of science a la Hull (1988). Yet the lists of the aims of evo-devo of Hall (2000) and Wagner, Chiu, and Laubichler (2000) map almost one-to-one to each other.

[7] "The reason why competition, selfish genes, struggle, adaptation, climbing peaks in fitness landscapes, doing better and making progress, are so importaqnt as metaphors in neo-Darwinism is because they make sense of evolution in terms that are familiar to us from our social experience in our culture" (Goodwin 1994: #).

[8] Given the inflationary use of the term “paradigm” that followed its popularization by Thomas Kuhn, most philosophers of science has become wary of the term. The feature we have in mind was better captured in Kuhn’s rendering of the so-called “disciplinary matrix.” As a kind of scientific *Weltanschauungen*, disciplinary matrices are acquired largely implicitly during scientific education, in which the learning of “exemplars” — archetypical applications of symbolic generalizations or theories to phenomena — is of paramount importance. Commonness of vocabulary and “symbolic generalizations” notwithstanding, scientific communities with different exemplars will hold different theories, and hence will "view the world differently." Still according to Kuhn, depending on one’s exemplars one will also tend to ask different questions and hold different values. (For a critical assessment, see Suppe 1977: 138—151.) At the level of *Weltanschauungen* biological discourse is heavily imbued with metaphors. To the extent that they also function in the society at large (cf. above), Kuhn’s internalist picture of scientific communities as esoteric cultures must be corrected:

[9] Hooker (1994) has argued for this position in painstaking detail in the case of Piaget’s biology and genetic epistemology. In a similar vein, Amundson (1983) has shown for the debate between behaviorists and cognitivists in psychology that paradigmatic “package deals” are not necessarily as monolithic as they are often presented.

[10] Cf. Maynard Smith's (1998) concluding chapter 5, "Reductionists to the Right, Holists to the Left," whose moral is that "it pays to be eclectic in our choice of theories", being "reductionist in one context and holist in another" (p. 45).

[11] Gould omits to credit Wimsatt's [1980] analysis of the explanatory impotence of "genetic bookkeeping" accounts.

[12] Homology, in its most evolved form, is characterized by an increasing independence from the underlying developmental, molecular, and genetic processes that led to the first appearance and subsequent fixation of basic individual homologues (*autonomization* — Müller and Newman 1999). The same phenotypic endpoint can be reached via different developmental pathways, and these pathways have changed importantly in the case of structures that are clearly homologous (Hall 1995). Autonomization of homologues is a consequence of a decoupling between genetic and morphological evolution, "Homologues, the design units of the phenotype, transcend their underlying molecular, epigenetic, and genetic constituents and assume an independent, organizational role in morphological evolution. With their integration into the bauplan of a phylogenetic lineage, homologues take on constructional identity and come to act as accretion points of further structural organization. They can be understood as 'attractors' of morphological design (Striedter 1998; Müller 1999), around which more design is added, and will be conserved even in the face of changing adaptive conditions. Therefore, at this autonomized stage, homologues are more influential for the further path of morphological evolution than the primary generic conditions underlying their origin and the biochemical circuitry that controls their developmental formation" (Müller 2002).

[13] We agree with Gilbert (2001b) that "not all parts of developmental biology and not all parts of evolutionary biology are involved in these new unions," although we do not share his exclusive focus on developmental genetics and population genetics. The situation is actually more complicated since "paleontology, morphometiics, QTL mapping, ecology, life history strategy research, and functional morphology" — and, we would add, biophysics — are also involved. If evo-devo is taken to include ecological considerations, thist list must be even further expanded (Gilbert 2001a).