

Weismann Rules! OK? Epigenetics and the Lamarckian temptation

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Received 23 March 2006; accepted in revised form 24 March 2006

Key words: Acquired characters, Epigenetics, Lamarckism, Neo-Darwinism, Peloric, Weismann

Abstract. August Weismann rejected the inheritance of acquired characters on the grounds that changes to the soma cannot produce the kind of changes to the germ-plasm that would result in the altered character being transmitted to subsequent generations. His intended distinction, between germ-plasm and soma, was closer to the modern distinction between genotype and phenotype than to the modern distinction between germ cells and somatic cells. Recently, systems of epigenetic inheritance have been claimed to make possible the inheritance of acquired characters. I argue that the sense in which these claims are true does not challenge fundamental tenets of neo-Darwinism. Epigenetic inheritance expands the range of options available to genes but evolutionary adaptation remains the product of natural selection of 'random' variation.

In *Evolution in four dimensions (EFD)*, Jablonka and Lamb present, what they believe is, a radical challenge to “the gene-centered version of neo-Darwinism that has dominated biological thought for the past 50 years” and to “the usual version of Darwin’s theory of evolution, which is that adaptation occurs through natural selection of chance genetic variations” (*EFD*, p. 1). Their challenge takes the form of evidence that there is more to heredity than genes; that some hereditary variations are nonrandom in origin; that some acquired information is inherited; and that evolutionary change can result from instruction as well as selection. The four dimensions of Jablonka and Lamb’s title are systems of genetic, epigenetic, behavioral, and symbolic inheritance. My comments will focus on the second dimension of epigenetic inheritance, because this is my area of expertise.

The term *Epigenetics* had two independent origins in the twentieth century, but this dual origin has not been widely recognized and the two meanings have become conflated (Haig 2004). Waddington (1942a) used epigenetics to refer to the causal processes of development, with an emphasis on interactions among genes and between genes and the environment. Nanney (1958) used epigenetic to describe systems of cellular heredity that were not based on the DNA sequence. Epigenetic mechanisms, in the latter sense, can involve purposeful modifications to an organism’s own genetic material in response

to environmental or other stimuli. Jablonka and Lamb (1989, 1995, 2002, *EFD*) and others (Monk 1995; Varmuza 2003a) have therefore argued that heritable epigenetic modification of DNA in the germline makes possible a form of Lamarckian inheritance. This inference has been described as “subversive” (Jablonka and Lamb 2002) and as a “renaissance of heresy” (Varmuza 2003a).

Neo-Darwinism

Neo-Darwinism means different things to different people, but the term was originally employed as a label for the uncompromising rejection of the inheritance of acquired characters by August Weismann and his followers. Romanes (1888) coined the adjective Neo-Darwinian to refer to a doctrine with which he disagreed, and since that time there have probably been more critics of neo-Darwinism than there have been self-described neo-Darwinists (although I am happy to accept the label for myself). In Romanes’ view, Weismann wished to establish “for natural selection a sole and universal sovereignty which was never claimed for it by Darwin himself.” Romanes objected to the description of this doctrine as Darwinism because Darwin himself was prepared to accept an evolutionary role for the effects of use and disuse. “There is no need to confuse the issues by the use of historically inaccurate terms. The school of Weismann may properly be called Neo-Darwinian: pure Darwinian it certainly is not.”

Weismann’s rejection of the inheritance of acquired characters was based on his concept of the germ-plasm.¹ In each generation, the body develops from a single cell. Such cells contain a substance, germ-plasm, that “has remained in perpetual continuity from the first origin of life” (Weismann 1891, p. 105) and that resides in the chromatin of the cell nucleus. The germ-plasm is composed of ‘ids.’ Each id contains all the determinants necessary to produce a complete individual.² Heritable changes in a body’s form must originate indirectly from

¹ My discussion of Weismann’s ideas is based on Weismann (1891, 1893, 1904). These are works in English, rather than Weismann’s native German. Weismann, himself, warned of shifts in nuance that could arise from a reliance on translations. When Herbert Spencer (1893) complained about Weismann’s facile use of the phrase “it is easy to imagine ...,” Weismann (1893) objected that the phrase was not his but “a somewhat too free translation of various phrases in the original German.” One of these phrases “so könnte man immerhin daran denken dass...” would, in Weismann’s opinion, have been better, if somewhat inelegantly, translated as “one could perhaps even think to explain this by assuming ...”.

² Weismann’s ‘id’ survives in haploid (single id) and diploid (double id) (see Strasburger 1894, 1906).

changes in the determinants, not directly from changes in the body itself.³ If the determinants are not tiny replicas of the parts determined, how could a change in a part cause a change in the part's determinant such that the acquired character was faithfully re-created in subsequent generations? An extended quotation will make Weismann's reasoning clear:

“I further believe that hardly any one would maintain that it is impossible for the reproductive organs to be influenced by correlation. But this is very far from the admission that such changes would occur in the germ-cells as would be necessary for the inheritance of acquired characters. For such transmission to occur it would be necessary for the germ-plasm (the bearer of hereditary tendencies) to undergo a transformation corresponding to that produced by the external influences; – such a transformation as would cause the future organism to spontaneously develop changes similar to those which its parent had acquired. But since the germ-plasm is not an organism in the sense of being a microscopic facsimile which only has to increase in size in order to become a mature organism, it is obvious that the developmental tendencies must exist in the specific molecular structure, and perhaps also in the chemical constitution of the germ-plasm itself. It therefore follows that the changes in the germ-plasm which would be required for the transmission of an acquired character must be of an entirely different nature from the change itself acquired by the body of the parent plant: and yet it is supposed that the former is produced by the latter as a result of correlation” (Weismann 1891, p. 414).

Here, and elsewhere, Weismann accepts the possibility of influences of the body and environment on the germ-plasm, but disputes that these influences can be the basis for the inheritance of acquired characters: “How could it happen that the constant exercise of memory throughout the lifetime, as, for instance, in the case of an actor, could influence the germ-cells in such a way

³ Weismann's argument against the inheritance of acquired characters is often claimed to be based on the early sequestration of germ-cells. However, this is a misrepresentation of his views: “It is evidently unimportant, as regards the question of heredity, whether this separation takes place early or late, inasmuch as the molecular constitution of the reproductive substance is determined before the beginning of development” (Weismann 1891, p. 74). Weismann recognized that “in most cases the generations of germ-cells do not arise immediately from one another as complete cells, but only as minute particles of germ-plasm. This latter substance, however, forms the foundation of the germ-cells of the next generation, and stamps them with their specific character” (ibid, p. 174). It was this immortal germ-plasm that was passed from generation to generation and that contained the determinants of somatic characters. Acquired characters could not be inherited because changes in the soma did not induce corresponding changes of the determinants.

that in the offspring the same brain-cells which presided over memory will likewise be more highly developed – that is, capable of greater functional activity? ... I can only compare the assumption of the transmission of the results of memory-exercise to the telegraphing of a poem, which is handed in in German, but at the place of arrival appears on the paper translated into Chinese” (Weismann 1904, p. 107).

One of Weismann’s most effective gambits against those who doubted the efficacy of natural selection was to find examples of exquisite adaptation that could not have evolved through the inheritance of the effects of use and disuse. Thus, Weismann argued that the intricate exoskeletons of insects could not have evolved by the effects of use and disuse, because the exoskeleton acquired its final, non-living form before becoming functional and could therefore not be modified by the effects of muscular action. Neo-Lamarckians viewed instincts as inherited habits, but many instinctive behaviors are performed once during the life-cycle and never practised. Similarly, the sterile workers of social insects had evolved elaborate behaviors and structures even though they never produced offspring to whom they could transmit acquired characters.

The major focus of Weismann’s critique was on the implausibility of the inheritance of acquired characters as a mechanism of heredity not its implausibility as an explanation of adaptation. The question of efficient or proximate causes was very much in the foreground. The question of final or ultimate causes was also present, but in the background. We tend to miss this emphasis of the late nineteenth-century debate because we now accept something close to Weismann’s theory of the continuity of the germ-plasm. Alternative models such as Darwin’s provisional theory of pangenesis, in which every part of the body gave rise to infinitesimal gemmules that coalesced in the germ cells, have been discarded. But it was Mendel and the double helix, rather than Weismann’s arguments that were decisive in carrying the field.

Jablonka and Lamb (*EFD*, pp. 16–40) see a continuity of error from Weismann’s neo-Darwinism (with its separation of germ-line and soma) through Modern Synthesis neo-Darwinism (with its separation of genotype and phenotype) via Molecular neo-Darwinism (with its ‘central dogma’ of a one-way flow of information from DNA to protein) into Selfish Gene neo-Darwinism (with its separation of replicators and vehicles). In their view, biological thinking about heredity and evolution is undergoing a revolutionary change that will dissolve the theoretical barriers that have been erected to deny information flow from the second to the first components of these dichotomies.

Epigenetics I

Waddington (1942a) introduced ‘epigenetics’ to refer to the study of the “causal mechanisms” by which “the genes of the genotype bring about phenotypic effects.” He believed that “Neo-Darwinism involves a breach between organism and nature as complete as the Cartesian dualism of mind and matter” and that an epigenetic consideration of evolution would go some way

toward healing the breach (Waddington 1953, p. ix)⁴. He objected to “The reigning modern view ... that, in nature, the direction of mutational change is entirely at random, and that adaptation results solely from the natural selection of mutations which happen to give rise to individuals with suitable characteristics” (ibid, p. 151).

Waddington’s concept of epigenetics invoked a causal role for the environment in developmental processes, and in the induction of alternative phenotypes. Thus, epigenetics could be considered to reopen the question of the inheritance of acquired characters. Waddington (1942b, 1959) proposed a mechanism, *genetic assimilation*, by which an acquired character (i.e., a character facultatively induced by an environmental stimulus) could come to be inherited (i.e., obligately expressed independently of the stimulus). Specifically, he envisioned a canalized developmental pathway that was initially evoked by an environmental stimulus to enhance an organism’s adaptedness. The canalized pathway and the adaptive trigger were themselves straightforward products of natural selection. If the environmental stimulus were sufficiently predictable, then natural selection would favor induction of the pathway by a genetic switch that acted before, and anticipated, the stimulus. The proposed mechanism is interesting, and may be important, but does not challenge any fundamental tenets of neo-Darwinism. The facultative response was encoded in the germ-plasm and there was a subsequent change to the germ-plasm such that the facultative response was now constitutive. When he is not lambasting neo-Darwinists, Waddington concedes as much:

“The process of selection for the ability of an animal to react adaptively to its environment, leading to the genetic assimilation of the adaptive character, provides us with a way of understanding how ‘acquired’ characters may become inherited without our having to suppose that the external conditions have been responsible for calling into being the necessary genetic determinants.” (Waddington 1953, p. 176)

Jablonka and Lamb also believe that “genetic assimilation and selection in stressful conditions have been central to adaptive evolution” (*EFT*, p. 281), but neo-Darwinian theory would not be fundamentally challenged if this contention were true.

Epigenetics II

Nanney (1958) was responsible for the second twentieth-century definition of epigenetics. Nanney was a critic of the triumphalist molecular genetics of his

⁴ Waddington (1968) defined Neo-Darwinism “in its strict sense” as “the mathematical models developed originally by Sewall Wright, Haldane, and Fisher, and elaborated since then by many later authors.”

day, rather than of neo-Darwinism. He chose ‘epigenetic’ to refer to mechanisms of cellular heredity that were not based on a “template-replicating mechanism” (i.e., were not based on semi-conservative replication of the double helix). From this beginning, epigenetic has come to refer to causes of heritable differences that are not dependent on changes in DNA sequence. The paradigmatic example of an epigenetic inheritance system is DNA methylation. Cells possess the molecular machinery for attaching methyl groups at particular sites on DNA (*de novo* methylation), of transmitting these methylation patterns to daughter cells (maintenance methylation), and of erasing the pattern of methylation either passively (by not expressing a maintenance methyltransferase) or actively (by mechanisms that are currently unknown).

Before considering the role of epigenetic modifications of the germ-plasm, it will be helpful to consider the role of epigenetics in somatic differentiation. The different cell types of a body possess the same DNA sequence but express different sets of genes and have different cellular phenotypes. Some of these differences are heritable (e.g., hematopoietic stem cells produce hematopoietic stem cells not hepatic stem cells). The process by which cells with a common genotype express different phenotypes is epigenetic (in both Waddington’s and Nanney’s sense of the term). A conventional neo-Darwinist interpretation would view these epigenetic mechanisms as ‘switches’ evolved by natural selection to enable genes to exhibit conditional behavior. By these means, genes can exhibit adaptive responses to environmental stimuli and can achieve a division of labor among cells. Not all epigenetic changes in somatic cells are adaptive, however. For example, the inappropriate activation or silencing of genes by epigenetic mechanisms has been implicated in various diseases, including cancer (Plass and Soloway 2002).

Two kinds of epigenetic modifications of germ-line DNA should be considered. The first kind consists of recurrent, reversible changes of epigenetic state (intergenerational switches). These can be considered analogous to the differentiation of alternative cell types by epigenetic mechanisms during somatic development. An example of such a switch is genomic imprinting, in which a gene’s epigenetic state is determined by its sex of origin. In this case, a past environment (whether the gene was present in a male or female body in the previous generation) determines whether or not a gene is expressed in the current generation. What is ‘best’ for a gene when maternally-derived is sometimes different from what is best for the gene when paternally-derived. Genomic imprinting allows genes to play conditional strategies that depend on whether they are in a maternal or paternal role (Haig 1997). The switch to a maternal or paternal state is a directed *non-random* change that is *acquired* during an individual’s life and *inherited* by its offspring.

One can imagine other kinds of adaptive epigenetic switches. Suppose that exposure of a parent to severe winters induces an epigenetic change in the germline that enables offspring to anticipate severe winters, perhaps by differentiating denser hair follicles, whereas repeated exposure to mild winters reverses this epigenetic effect. There are complications in how such a

mechanism would be implemented, given that each offspring has two parents, but one could, in principle, imagine such a mechanism evolving by natural selection.

A neo-Darwinist would make three points about epigenetic switches. First, the ability for a DNA sequence to switch epigenetic state should, at least in part, be a property of the DNA sequence itself, and, therefore, subject to natural selection on conventional mutations. Second, natural selection will eliminate switches with maladaptive effects but perpetuate, and refine, those with adaptive effects. Third, the additional 'information' represented by a DNA sequence's particular epigenetic state is repeatedly being reset. Thus, epigenetic switches do not involve cumulative, open-ended evolutionary change. Switches are wonderful tools that increase the options available to DNA sequences but, in themselves, should not challenge the beliefs of a neo-Darwinist. I prefer to think of heritable switches in epigenetic state as an expression of trans-generational *ontogeny*.

The second kind of epigenetic modification of the germ-line consists of more-or-less permanent epimutations that, once having occurred, are transmitted faithfully to future generations until the occurrence of the next epimutation. Such epimutations are potentially a source of long-term evolutionary information and of *phylogenetic* transformation, but are conceptually little different from genetic mutations. The foundational models of neo-Darwinism are older than the discovery of the double helix. Therefore, it is hardly surprising that these models are essentially neutral as to whether a heritable change is brought about by a change in DNA sequence or a change in cytosine methylation. If heritable epimutations resulted in phenotypic diversification in a genetically homozygous population, then those individuals with epimutations that enhanced their adaptedness to the local environment would leave more descendants and the favored epimutations would necessarily increase in frequency. The challenge to neo-Darwinism comes, not from the existence of epigenetic inheritance, but from the possibility that epimutations are directed rather than random. This is an issue to which I will return in a subsequent section.

Jablonka and Lamb (*EFD*, p. 114) consider life on the planet Jaynus where the DNA sequence remains unchanged but evolution proceeds by the accumulation of epimutations. On planet Earth, however, there are reasons to believe that long-term evolutionary information has accumulated largely, if not entirely, through changes in the DNA sequence, rather than in its epigenetic modifications. The first of these is the low-fidelity of epigenetic inheritance. Bennett-Baker et al. (2003) estimated that the rate of functional epigenetic mutation in somatic tissues was one to two orders of magnitude higher than the rate of genetic mutation. I know of no similar comparison of rates in the germ-line, but all indications are that the rate of mutation in the DNA sequence is much lower than the rate of epimutation. The high rate of epigenetic change is important because the level of achievable adaptive precision is limited by the fidelity of replication. Adaptation is constantly being degraded by copying errors and the higher the rate of errors, the larger the selective advantage that is

required to maintain previous adaptation. Thus, small selective advantages are unable to be maintained in the presence of low-fidelity replication. Therefore, significant adaptations are expected to be encoded genetically rather than epigenetically.

Jablonka and Lamb (*EFD*, p. 142) cite the peloric form of *Linaria vulgaris* as an example of a “fairly stable epimutation.” *Linaria vulgaris* normally has flowers with bilateral symmetry. In 1742, Linnaeus discovered a specimen of *L. vulgaris* with radially symmetric flowers that he called Peloria (Gustafsson 1979). Recently, Cubas et al. (1999) have shown that the peloric phenotype was due to a change of methylation at the *cycloidea* locus and not due to any change in the DNA sequence. At least, that is the way the story was sold to the editors of *Nature*. Linnaeus’ Peloria died but peloric plants were rediscovered at a nearby site in 1953 (Gustafsson 1979). Peloric plants have also been found scattered over most of Europe and have occurred spontaneously in cultivation (de Vries 1910). The peloric specimen used by Cubas et al. (1999) was obtained from the United Kingdom (see fine print in their Acknowledgements). No evidence was provided for an unbroken chain of provenance from this specimen back to Linnaeus’ plant, and this seems unlikely. The epimutation studied by Cubas et al. was highly unstable. Three out of five peloric F₂ individuals produced wild-type branches after several years growth in the greenhouse (see their Methods section). Genetic mutations at the *cycloidea* locus in a related species cause a peloric phenotype (Luo et al. 1996). Thus, it is highly unlikely that the British specimen was a descendant of Linnaeus’ specimen and there is no way of knowing whether Linnaeus’ plant had an epimutation or a mutation at the *cycloidea* locus. Bilateral floral symmetry has been derived several times independently from radial symmetry as an adaptation for specialized methods of insect pollination (Cubas 2004). Therefore, the peloric epimutation resulted in a loss of adaptation and a reversion to an ancestral symmetry, rather than the production of an evolutionarily novel structure.

A second reason for the primacy of the DNA sequence in the accumulation of long-term evolutionary information is its relative information density. A 1-kb DNA sequence is separated from 4,000 other sequences by the change of a single nucleotide, and the universe of possible 1-kb sequences that is open to evolutionary search is an astronomical 4^{1000} . The number of possible epigenetic states available to any particular 1-kb sequence is unknown, but is almost certainly many, many orders of magnitude smaller. For this reason, sequence-based evolution can achieve a specificity that is unattainable by known mechanisms of epigenetic change. From an evolutionary perspective, epigenetic variation is, for the most part, likely to be subservient to the evolving DNA sequence. That is, the machinery of epigenetic modification (DNA methyltransferases, histone deacetylases, etc.) is encoded by the DNA sequence and whether a particular sequence is subject to a particular epigenetic modification will be partly dependent on properties of the sequence itself.

The primacy of the DNA sequence as a source of hereditary information is suggested by the effects of inactivating the maintenance methyltransferase gene

(*Dnmt1*) in embryonic stem cells. These cells were able to proliferate, but could not maintain methylation patterns and were unable to form differentiated tissues. Therefore, cytosine methylation performs an essential function during development. However, re-introduction of *Dnmt1* into these cells restored the heritable transmission of methylation patterns through mitosis and restored the cells' ability to differentiate. Moreover, the transformed cells were able to colonise the germlines of chimeric mice and their DNA sequences could be successfully transmitted to normal fertile offspring (Tucker et al. 1996). Therefore, all of the information necessary to reconstitute the correct pattern of methylation appears to have been present in the DNA sequence, but required the presence of the appropriate DNA-encoded machinery for its expression. The initial inactivating mutation erased all the 'information' present in the pattern of methylation, yet none of this information was necessary to restore the 'message' transmitted through the germline.

Modern neo-Darwinists do not deny that epigenetic mechanisms play an important role during development nor do they deny that these mechanisms enable a variety of adaptive responses to the environment. Recurrent, predictable changes of epigenetic state provide a useful set of switches that allow genetically-identical cells to acquire differentiated functions and allow facultative responses of a genotype to environmental changes (provided that 'similar' changes have occurred repeatedly in the past). However, most neo-Darwinists would claim that the ability to adaptively switch epigenetic state is a property of the DNA sequence (in the sense that alternative sequences would show different switching behavior) and that any increase of adaptedness in the system has come about by a process of natural selection. Variant sequences that undergo maladaptive switches do not leave descendants whereas variant sequences that fortuitously undergo adaptive responses to environmental stimuli are perpetuated and become the foci for further adaptive refinement through the natural selection of random mutations.

The inheritance of acquired characters

“... it has become evident to me that the meaning of ‘acquired character’ is elastic to an amazing degree, capable of marvellous contraction or expansion to suit the individual needs of any and all controversialists, be they NeoDarwinian or NeoLamarckian.” (Nutting 1892)

For most biologists and the general public, a Lamarckian is someone who believes in “the inheritance of acquired characters.” But what does this phrase mean? Different implicit definitions of ‘acquired’ can allow Dawkins (1987) to emphatically deny the inheritance of acquired characters and Varmuza (2003b) to equally emphatically affirm their inheritance. Varmuza, like Waddington before her, is a developmental biologist and interprets terms such as “acquired,”

“inherited,” “adaptation,” and “cause” with subtly different connotations from those which would be assumed by a neo-Darwinist addressing the evolutionary (phylogenetic), rather than developmental (ontogenetic), origins of adaptation.⁵ I will therefore commit ‘heresy’ and concede that there is a sense in which epigenetics allows the inheritance of acquired characters and that the characters thus inherited can increase the adaptedness of an organism to its environment. However, I will argue that this sense does not contradict fundamental tenets of ‘orthodox’ neo-Darwinism.

Suppose that dietary supplements of folate cause epimutations of germ-cell DNA and these epimutations are inherited by offspring (Waterland and Jirtle 2003). An acquired character has been inherited. However, if an epimutation is an acquired character merely because it is induced by the environment, then a genetic mutation, caused by exposure to radiation or a chemical mutagen, is also an acquired character. Under such a definition, the inheritance of acquired characters becomes no more than a statement that some causes of variation are heritable, one of the fundamental assumptions of Darwinism.

Now consider the case of genomic imprinting. A gene *acquires* a particular methylation pattern when it passes through a male germ-line and a different pattern when it passes through a female germ-line. These patterns are *inherited* by offspring and influence where and when the gene is expressed. The process is directed, rather than random. An acquired character has been inherited but, from a longer-term perspective, the methylation of DNA merely alternates between the maternal and paternal pattern, without ongoing evolutionary change. Finally, consider Waddington’s model of genetic assimilation. A character that was conditional on an environmental stimulus comes to be expressed in all individuals, independently of the environment. An acquired character has been transformed into an inherited character, even though all heritable changes originate as germ-line mutations.

⁵ *Adaptation* has historically referred to two processes in biology. The first process is the adaptive response of an individual organism to its particular environment (adaptation₁). A classic example is the hypertrophy of the forearms of the village blacksmith. Another is darkening of the skin in response to ultraviolet radiation. Such adaptive responses are often considered to be acquired characters (or characters that are induced by the environment). The second process is the change in the heritable properties of organisms over evolutionary time that makes organisms more suited to their environments (adaptation₂). Neo-Darwinists believe that phylogenetic adaptation (adaptation₂) occurs by natural selection of random genetic variation and that among the products of natural selection are processes of ontogenetic adaptation (adaptation₁). Neo-Lamarckians believe that ontogenetic adaptation (adaptation₁) can be a source of phylogenetic adaptation (adaptation₂). A nuanced position is that adaptation₁ facilitates adaptation₂. For example, new blood vessels grow to where they are needed because hypoxic cells release a signal that enhances vascular growth (adaptation₁). This mechanism ensures that an organ will automatically be supplied with blood vessels whenever it evolves a new size or shape (adaptation₂) (Kirschner and Gerhart 2005; pp. 169–171). As a final snarl in this semantic tangle, characters produced by adaptation₁ or adaptation₂, especially by the latter, are called *adaptations* (adaptation₃). There is plenty of scope for mutual misunderstanding in discussions of adaptation.

None of these examples involve the kind of direct inheritance of somatic changes that Weismann criticized, and that Dawkins denies, but all can be legitimately described as the inheritance of acquired characters because the latter phrase has no universally accepted meaning. If I could choose, I would ban discussion of ‘the inheritance of acquired characters’ and talk separately of the inheritance of mutilations, the inheritance of the effects of use and disuse, the inheritance of methylation patterns, the acquisition and inheritance of DNA-bearing plasmids, and so on. If this step were taken, one would find broad consensus on most questions of fact: mutilations and the effects of use and disuse are not inherited⁶; some methylation marks are inherited. For each proposed mechanism, one could then address substantive questions such as whether inheritance is restricted to mitotically-dividing cells or can pass through meiosis; whether the mechanism results in an accumulation of evolutionary information or merely an alternation among a limited number of predetermined states, and so on.

Jablonka and Lamb proudly identify themselves as modern Lamarckians. Three quotations will give the flavor of their version of Lamarckism. First, “Darwinian evolution can include Lamarckian processes, because the heritable variation on which selection acts is not entirely blind to function; some of it is induced or ‘acquired’ in response to the conditions of life” (*EFD*, p. 102). Second, “For most biologists, ... when the heredity material (or process) is not constant from generation to generation, but can be modified by the effects of the environment or the organism’s activities – it qualifies as Lamarckian inheritance” (*EFD*, p. 229). Third, “whenever heredity is ‘soft,’ in the sense that what is inherited is molded by environmental and developmental factors, it is considered ‘Lamarckian’” (*EFD*, p. 361). Their Lamarckian challenge to neo-Darwinism appears to make two interrelated claims: that the environment and an organism’s activities can influence what is inherited; and that some heritable variation is purposeful rather than random. The first claim has been addressed above in my discussion of the inheritance of acquired characters. I turn to the question of purpose in the next section.

Evolutionary teleology

“But the philosophical significance of natural selection lies in the fact, that it shows us how to explain the origin of useful, well-adapted structures purely by mechanical forces and without having to fall back on a

⁶ Sonneborn’s studies of cortical inheritance in ciliates (see *EFD* pp. 121–122) provide an unusual example in which mutilations are inherited. ‘Inheritance’ of an inverted row of cilia in these experiments probably involves a direct templating mechanism, with the ‘acquired’ character transmitted directly from mother to daughter cell without an intervening process of ‘ontogeny’ during which the character is not present.

directive force. We are thus for the first time in a position to understand, in some degree, the marvellous adaptation of the organism to an end, without having to call to our aid any supernaturally intrusive force on the part of the Creator.” (Weismann 1904, p. 55; emphasis in original)

“When all four inheritance systems and the interaction between them are taken into account, a very different view of Darwinian evolution emerges. It is a view that may relieve the frustration that many people feel with the prevalent gene-centered approach, because it is no longer necessary to attribute the adaptive evolution of every biological structure and activity, including human behavior, to the selection of *chance* genetic variations that are *blind* to function.” (EFD, p. 2; emphasis added).

Jablonka and Lamb’s frustration with neo-Darwinism is with the pre-eminence that is ascribed to undirected, random sources of heritable variation. The meaning of ‘random mutation’ is frequently misunderstood, however. The variation generated by mutation is said to be random if it is not directed to produce a predetermined adaptive end. However, the focal sequences around which variation is generated occur in highly non-random locations in the immense realm of sequence space because of the cumulative effects of past natural selection. The non-randomness of a focal sequence can be considered to be a measure of the accumulation of evolutionary information. The source of this information is the environment, broadly construed.

Modern neo-Darwinists posit a two-way flow of information between genotype and phenotype that is an implicit consequence of the *recursive* nature of replicator dynamics. Effects can be causes. Genotypes interact with the environment to produce phenotypes and then phenotypes interact with the environment to determine which genotypes are replicated to become the focus for the next round of ‘random’ mutation. By this process genotypes come to *refer* to the environment and to have *purposes* with respect to the environment.

There is an irony in appeals to Lamarckian processes to find a purposefulness that is lacking in neo-Darwinism, because I am yet to hear a coherent explanation of how the inheritance of acquired characters can, by itself, be a source of intentionality. Rather, the intentionality of Lamarckian systems is always built into the system, and must arise by some other process. I find Dennett’s concepts of ‘cranes’ useful in this context. Dennett defines a crane as

“... a subprocess or special feature of a design process that can be demonstrated to permit the speeding up of the basic, slow process of natural selection, *and* that can be demonstrated to be itself the predictable (or retrospectively explicable) product of the basic process.” (Dennett 1995, p. 76)

Systems of adaptive directed mutation and epimutation exist, but these are cranes. How else could their purposefulness have originated except by natural selection of ‘random’ mutations? Our ability to learn from trial and error, and from observing others’ behavior, is a very powerful crane that generates purposeful behaviors without the wastefulness of natural selection. But the ability to learn and the kinds of things that we can and cannot learn are themselves products of natural selection. There is no reason, in principle, why a system for the inheritance of acquired characters cannot evolve by natural selection, given a strong enough selective advantage and appropriate genetic variation. One can imagine a system that detects the hypertrophy of a blacksmith’s arms, signals this hypertrophy to spermatogonia in his testes, and there causes an epigenetic change that results in his sons possessing more muscular forearms. But, how could such a system evolve, if not by natural selection? There is no problem with a telegram being sent in German and delivered in Chinese if the message passes through the hands of a German–Chinese translator in transit.

I was familiar with much of the evidence presented by Jablonka and Lamb, yet considered myself, and still consider myself, to be a rather orthodox neo-Darwinist. Jablonka and Lamb accept that the intentionality of the ‘instructional’ systems they describe originates in natural selection, at some level, but consider themselves heretical neo-Lamarckians. Most of our disagreements are matters of preference, of how we choose to define terms, and of the particular ‘spin’ we choose to put on evidence. But such choices can have important consequences for how one understands biological systems. Jablonka and Lamb want to get rid of hard distinctions between soma and germ-line, replicators and vehicles, physiology/development and evolution, genotype and phenotype, ontogeny and phylogeny, proximate and ultimate explanations. These artificial distinctions, they believe, obscure more than they reveal. Questions of development, heredity, and evolution are too interdependent to separate (*EFD*, p. 102). Others may believe that the distinctions are still important to promote clarity of thinking. It behoves all evolutionary biologists to periodically question the utility of their basic conceptual tools.

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