

This is a Pre-Print version of the following article:

Luca Chiapperino and Francesco Panese, 'On the Traces of the Biosocial: Historicizing "Plasticity" in Contemporary Epigenetics', *History of Science*, 18 November 2019, 42, <https://doi.org/10.1177/0073275319876839>.

1 On the traces of the biosocial: historicizing plasticity in contemporary 2 epigenetics

3 Introduction

4 In current epigenetics, the notion of biological 'plasticity'¹ plays a pivotal role. The interplay
5 among the genome, the epigenome and the environment is deemed capable of providing
6 explanations for the aetiology of most common diseases and life-course health trajectories.²
7 Plasticity thinking helps to legitimate normative evaluations of the alleged responsibilities of
8 individuals and collectives (including governments) to protect the epigenomes of present and
9 future generations.³ Modifications and adaptations of the body mediated by environmental
10 stimuli, social conditions, and life-course experiences extend molecular understandings of both
11 healthy and diseased phenotypes to encompass epigenetic effects potentially passed to future
12 generations.⁴ The biographies and biologies of multiple generations seem to be linked by means
13 of malleable and stable epigenetic marks,⁵ which revive the centrality of plasticity in evolutionary
14 thinking under the heading of epigenetically acquired characters.⁶ Plasticity is, in other words, an
15 operational concept that both inspires a series of cognate – yet distinct – research programs in
16 epigenetic sciences and calls for a re-negotiation of the traditional boundaries between the social
17 and biological understandings of (human) life. By dissecting the plastic adaptations of our biology
18 to its material and social environments, contemporary epigenetics broadens the horizon of the
19 life sciences to a potentially *biosocial* epistemology⁷ that challenges the irreducible oppositions
20 between social and biological understandings of life.

21 In this paper, we build upon historico-epistemological analyses of plasticity across the 19th and
22 20th centuries in order to distinguish among uses of this notion in contemporary epigenetics. By
23 digging into this diachronic phase of plasticity thinking, we highlight a series of historically-
24 situated understandings and pragmatic dimensions of this notion. These different versions of
25 plasticity allow us, in turn, to discern synchronically how plasticity in epigenetics encompasses
26 distinct visions and experimental practices that make sense of the reciprocal entanglement of
27 (human) bodies and their (material and social) environments. Parallel to this analysis of the
28 'epistemic space'⁸ of plasticity from the 19th century onward, we show how these distinct modes
29 of understanding body-environment relationships also constituted conceptual, representational,
30 and experimental resources for understanding the entanglement between life as biological and
31 socially situated phenomenon. These different traces of the biosocial *ante litteram*, we conclude,

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1 may be at play also in contemporary epigenetics and post-genomics and thus constitute an entry
2 point onto the assumptions, values, (social) ontologies and political leanings populating
3 contemporary life sciences.

4 As to the *diachronic* dimension, we reconstruct the role of plasticity thinking in the *longue durée* of
5 debates about phenotypic development and evolution in modern biology (i.e. from the 19th
6 century onwards). Plasticity thinking, we argue, structured and directed epistemic practices
7 towards distinct understandings of how human biology acts in concert with environmental
8 influences. Specifically, our analysis describes four distinct phases in plasticity thinking across the
9 19th and 20th centuries: (i) plasticity as chemical modification of the body by its milieu; (ii)
10 plasticity as *explanandum* for the modifications of life's ontogenetic and phylogenetic substrates;
11 (iii) plasticity as mechanistic process in need of distinct explanations in ontogeny and phylogeny;
12 and (iv) plasticity as responsive potential to perturbations of a complex genetic system of
13 development. These different conceptions of plasticity, we argue, reveal distinct interpretations of
14 how the material substrate of our biology is permeable and susceptible to its environments. This
15 element, as we shall see, also offers the opportunity to show how plasticity was an epistemic
16 resource to interpret, demarcate and govern the boundaries between biological and social aspects
17 of (human) life, and consequently allows us to describe different traces of the biosocial in its
18 historical and epistemological trajectory.

19 With regard to the *synchronic* dimension, we show how these four ways of interpreting and
20 operationalizing plasticity can be used to characterize and distinguish present uses of this notion
21 in epigenetic biosciences. In this respect, our work differs from a history of why and how
22 plasticity thinking re-emerged in recent biology.⁹ Rather, our paper aligns with the current wave
23 in history, philosophy and social studies of science which interprets and criticizes contemporary
24 biology by situating it in a longer history¹⁰. To do so, we draw several parallels between past
25 characterizations of plasticity and its uses in epigenomics, behavioral epigenetics, environmental
26 epigenetics and molecular epidemiology. Our work highlights how epigenetic views of the plastic
27 body are a far more complex, historically tangled and idiosyncratic construction than it is
28 generally believed.¹¹ While some authors have argued that epigenetics constitutes a novel
29 discovery of the body's permeability, memory and porosity,¹² our analysis counters this belief on
30 historical grounds and provides a typology of plasticities as long-standing heuristics of body-
31 environment relationships that currently co-exist in epigenetics. In this respect, our paper may be
32 read as an illustration of how the vital traffic bodies-milieus in contemporary life sciences is

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1 actually a panoply of distinct epistemic programs and, potentially, biosocial strategies for
2 governing and making sense of this plastic nexus.

3 Certainly, our focus on the similarities across temporally distant mobilizations of plasticity is
4 inescapably defective as to the sharp contrasts between the styles of reasoning¹³ in contemporary
5 molecular biology and pre-genetic biological thinking. Yet, we argue, our work can be useful both
6 (i) to illuminate some of the preconditions that make thinking the idea of plasticity possible
7 today,¹⁴ and (ii) to perform "a historical dissolution of self-evident identities"¹⁵ among cognate
8 practices of knowledge-making in contemporary biology. As to the former, our paper calls for a
9 critical approach to the alleged 'revolution' ascribed to epigenetics in its societal circulation.¹⁶ Our
10 historical and epistemological analysis of plasticity capitalizes on "the interpretative purport of
11 [historians'] achievements"¹⁷ in order to question epigenetics' allegedly novel openings towards a
12 biology of body's permeability, memory and porosity. Contrary to this view, we show that these
13 concepts have been a constant matter of discussion and uncertainty (at least) since the onset of
14 biological thinking as an organized domain of knowledge¹⁸. As to the latter, the identification of
15 various theorizations (and operationalizations) of body-environment relations in contemporary
16 epigenetics shows the diverse explanatory functions plasticity affords in the epistemic landscape
17 of post-genomics. Thanks to the comparisons we draw with historically-situated interpretations
18 of plasticity, our paper offers a counter-point to the prevailing assumption that the origin of the
19 different scientific programs in epigenetics can be found in the ideas of Conrad Hal Waddington
20 – the widely recognized founder of 'epigenetics'.¹⁹ In contrast to this view, the historical cases we
21 present allow us to describe how distinct epistemologies of plasticity co-exist alongside
22 Waddington-inspired research programs in current epigenetics. Fleshing out these historical
23 ramifications animating the present, we argue, reveals a fundamental epistemological
24 disagreement at the basis of the controversies around the definition of the scope and epistemic
25 priorities of epigenetics: how to reconcile the contemporary epistemologies of plasticity that hold
26 epigenetic marks capable to bear the material impression of the environment with those
27 grounded on a strong view of (epigenetic) plasticity as operating under genetic control?
28 Finally, our work offers also the opportunity to recast in a longer history the biosocial openings
29 ascribed to contemporary epigenetics.²⁰ Plasticity thinking, in the diachronic trajectory we
30 investigate, did not simply constitute the epistemic construction of an understanding of the
31 reciprocal modulation of organic substrates and their (material and social) environments in
32 development, the life-course and evolution. Rather, this notion played also a pivotal role to

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1 embed the body's biology within coeval socio-political contexts. Plasticity provided in fact a
2 repertoire of mechanisms and explanations that could account for a fundamental hybridity
3 between our biological and social existence – with the resulting consequence that it also
4 constituted the basis to inspire political action. These traces of the biosocial *avant la lettre*, we
5 conclude, raise the question as to how similar concerns may be raised by contemporary debates
6 in and around epigenetics.

7 **Part 1 – The diachronic dimension: 'plasticity' across the 19th and 20th centuries**

8 The idea of plasticity has a very long history²¹ extending back to 'environmental theories' of
9 health and inheritance of acquired characters in Hippocrates.²² It is already found, for example, in
10 Plato, who attempts to account for the memory and the mind as substances molded by
11 perception and thought.²³ Furthermore, as we learn from philosopher Catherine Malabou,²⁴ the
12 idea of plasticity in Aristotle designates a twofold process of receiving and giving form, which is
13 exemplified by the phenomenon of perception as both passivity of the senses (i.e. the inscription
14 of an alterity in the sensible substratum) and realization of the potential of the perceptive faculty
15 itself (i.e. sensing as the achievement of the natural function to sense the external world).

16 Between these two poles of passive molding/imprinting and active auto-
17 determination/actualization of potentiality lies the semantic space of plasticity which we will
18 investigate in the remainder of the paper. Yet, from the Greek adjective πλαστικός (*plastikos*) to
19 cognate notions such as 'plasma' in 19th century theories of heredity and contemporary
20 mobilizations of plasticity in epigenetics, what we can observe is less the supposedly very old
21 stabilization of one concept than the historically-situated attempts to answer a cardinal question:
22 how to account for the reciprocal modulation of organic substrates and their (material and social)
23 environments? Answering this question has, in other words, taken a far from linear route that is
24 specific to times²⁵ and places²⁶ of scientific as well as humanistic²⁷ interrogation, and whose
25 reconstruction goes beyond the scope of the present analysis. However, it is worth underlining
26 here why focusing on the diachronic dynamics of plasticity thinking across the 19th and 20th
27 centuries is pivotal to a critical uptake of this notion in contemporary epigenetics.

28 First, the 19th century marks the stabilization of questions related to plasticity as matters of
29 methodical observation. In an attempt to render the dominant Hippocratic-Galenic views in
30 medicine less dogmatic, 18th century European medical schools shifted towards theoretical
31 refinement and accumulated evidence, which fostered more sophisticated explanations of disease,
32 adaptation and their inheritance. At the dawn of the 19th century, the emergence of disease and its

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1 transmission through generations comes to be approached in terms of plausible physiological
2 causal routes and through the accumulation of case histories, which replace the traditional
3 explanations grounded on familial, group or local causes.²⁸ As argued by Müller-Wille and
4 Brandt²⁹ the 19th century marks the progressive assemblage of an epistemic space of
5 representational, conceptual and practical tools in biological thinking, which gradually turned into
6 the consolidation of the 'epistemic objects' of the dedicated discipline of genetics with its defined
7 spaces, concepts, standards and technologies. Following the diachronia of plasticity in this period
8 is thus a way to restrict our analysis to the moments in which the long history of plasticity
9 thinking³⁰ bifurcated into a construction and product of an (increasingly) *organized episteme*.

10 Second, the interest in plasticity thinking across the 19th century (and beyond) can also be
11 explained by the social and political conditions that stand in a dynamic of co-production with the
12 episteme of that time. The 19th century approaches to plasticity we analyze are in fact coeval to
13 the emergence of the preoccupation on the side of institutions and the state to make populations
14 healthier. In this respect, a focus on this historical period enables a description of how plasticity
15 thinking has been recruited to solidify "mechanisms, techniques and technologies of power" over
16 the body of a population.³¹ More specifically, the 19th century offers the possibility of observing
17 not only one period in which the body is cast as an entity open and permeable to its
18 surroundings. Rather, 19th century cases shed also light on the explicit epistemic construction of
19 the body as a socially determined phenomenon to be governed by means of intervention on the
20 social and material milieu. As we will see later, conceptions of the plastic body across the 19th
21 century (and beyond) mark the debut of institutional, administrative and political actions directed
22 at intervening³² on the effects of social and material environments for ontogeny and – later in the
23 century of heredity³³ – phylogeny. In other words, the 19th century offers the opportunity to
24 historicize plasticity as a way to give shape to biosocial understandings of the human condition,
25 which have implications for the biopolitical governing of the body *qua* biological and social
26 entity.

27 Restricting our focus to the 19th and 20th centuries certainly overlooks the continuities and
28 analogies that run throughout the history of plasticity from Hippocrates to theories of
29 pathological heredity and degeneration.³⁴ Furthermore, the selection of cases we present here is
30 meant only to extrapolate key themes in the last two centuries of plasticity thinking and not to
31 provide a comprehensive analysis of the complex developments related to this notion across this
32 same period.³⁵ Yet, we have selected these cases because they enable us to unpack major

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1 epistemological differences among alternative strands of contemporary epigenetic research. Our
2 case studies are particularly useful in that they highlight distinct epistemo-political avenues of
3 plasticity thinking, which mark the distinctions among some of the most relevant approaches in
4 current epigenetics. By subjecting the body-environment porosity to methodical investigation, by
5 setting up factual elements for political reforms and the functioning of nascent institutions, and
6 by theorizing the need to address plasticity as a social problem for present and future generations,
7 the theorizations of plasticity over the 19th and 20th centuries we analyze offer a privileged entry
8 point on the 21st versions of these very same concerns in epigenetic biosciences.

9 *1.1 French public hygiene: a paradigm of chemical alteration of the body*

10 By the end of the 18th century, the problematization of the human body as an entity modified by
11 its environments takes an important epistemo-political turn in several national contexts.³⁶ Here,
12 we focus on the case of France, whose cultural tradition was dominated by a mechanistic
13 conception of biology, which postulated a materialist and deterministic understanding of the
14 body, its environments and their relationship.³⁷ Within this context, the notion of 'milieu' played
15 a pivotal role to theorize processes of evolutionary transformations in their well-known
16 Lamarckian formulation: "*les animaux doivent leur forme générale aux influences du milieu dans lequel ils*
17 *habitent*"³⁸ Yet, it is by means of the coeval³⁹ hygienist movement that systematic theories aimed
18 explicitly at understanding "the influence of physical things on man" became concrete elements
19 for political strategies to promote "the means of preserving health."⁴⁰

20 These two quotes are in fact the subtitle of the founding treaty "Elements of Hygiene" (1802) by
21 Etienne Tourtelle (1756-1801). Three elements are particularly interesting in the case of French
22 hygienists. First, the human body is conceived as a metabolic chemical entity – before the term
23 metabolism was coined⁴¹ – whose state is 'modified' by its exposure to external factors, such as
24 the 'atmosphere:'

25 The human body, in the midst of the atmosphere, does not have to be thought merely as a mass upon
26 which atmospheric influences act physically, but also as a *blend* within which chemicals bonds are
27 established between its principles and those of the air. At last, as organized body [...], *the human body*
28 *receives particular modifications from the atmosphere.*⁴²

29 Second, the hygienist movement formulates and renders operational a taxonomy of chemical
30 alterations of the body promised to a long fortune. Through the identification of discrete
31 "matters of hygiene" whose chemical action on the body renders them "health modifiers,"⁴³
32 hygienists isolate distinct patterns of body-milieu interaction on which to act in order to preserve
33 health:

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- 1 *Circumfusa*: the action that bodies exert upon us, like the atmosphere, the places, water, climate.
- 2 *Applicata*: the things that are applied to the surface of our bodies, such as clothes, baths, frictions,
- 3 cosmetics, etc.
- 4 *Ingesta*: the ingested substances, such as food and drinks.
- 5 *Excreta*: all that relates to excretions.
- 6 *Gesta*: physical exercise and any voluntary action.
- 7 *Percepta*: the influence that our perceptions exert upon the animal economy by means of the
- 8 encephalon and our nervous system.⁴⁴

9 Inspired by the nascent chemical episteme of Antoine-Laurent de Lavoisier (1743-1794),⁴⁵ French
10 hygienism constitutes a strong research program devoted to the establishment of an
11 environmental and social aetiology of disease. In this program, diseases are described as
12 mechanical and chemical phenomena emerging at the intersection of external actions and internal
13 effects. The methodical collection of statistics about the living and working conditions of Parisian
14 workers, as well as the recollection of systematic observations about the effects of their *milieux* on
15 health constitute a theorization of the importance of discerning healthy and unhealthy bodily
16 states as the product of material and social determinants of pathogenic alterations. Needless to
17 say, this view of disease aetiology also has a bearing upon the conceptions of sanitary therapy
18 developed by hygienists.

19 In fact, a third element worth noting in operationalizations of plasticity thinking in the hygienist
20 movement relates to their approach to the management of these health modifiers. Their
21 taxonomy of chemical alterations of the body gradually crystallizes in a political-moral duty to
22 protect individuals by acting on the milieu; less so to restore the health of individuals than to
23 preserve them from external threats. Besides the fact that therapeutics were poorly developed in
24 this period, several concurring factors contributed to the focus of hygienists on actions addressed
25 at the reducing the pathogenicity of living conditions. Primarily, medical approaches of the time –
26 in France as well as in other contexts⁴⁶ – largely privileged the attendance to the manifestations
27 rather than the causes of disease on the states of mind and the body. Going under the label of
28 “expectant medicine,”⁴⁷ this approach to the treatment of diseases consisted in the recognition of
29 the ‘natural’ tendency of the body towards cure. Thus, the treating role of the physician consisted
30 more in accompanying the body’s intrinsic vital actions to restore health (e.g. through the
31 elimination of external threats), rather than in the administration of artificial remedies to
32 eliminate morbid states. Secondly, before the advent of the Third Republic produced a new
33 political elite with a large component of doctors, the first actors and theoreticians of hygiene in
34 France were liberal chemists who tended to oppose the interference of the state in private affairs
35 such as individual health and treatments. For these reasons, hygienists implemented what

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1 philosopher Gérard Jorland has called a “socio-clinical”⁴⁸ approach to the protection of
2 populations from the threats of their environments. Similarly to what characterized the
3 emergence of public health in other national contexts,⁴⁹ French hygienists did not focus on the
4 treatment of disease, but rather implemented ‘treatment’ strategies for the population that
5 consisted in the systematic removal of all potential factors of morbidity from the living
6 conditions, habits and material urban environments of citizens. For instance, the nutrition of
7 workers constituted the object of medical interventions directed at improving its quality, its
8 cleanliness, its distribution and its nutritional value all for the purpose of preventing the
9 development of diseases in this population:

10 Human beings are surrounded by dangers; their frail existence is incessantly threatened by thousands
11 of destructive plagues; its organization subject to the trial of alterations that expose them to a
12 multitude of aches at every moment.⁵⁰

13 Thus, at the beginning of 19th century we observe that the hygienist movement provided an
14 elaborate conception of the reciprocal modulations of bodies and their environments that is
15 grounded in mechanistic explanations formulated in the grammar of nascent modern chemistry.
16 This operationalization of a plastic conception of the body instructed, in turn, institutionalized
17 practices of sanitation, which constituted a historical precedent of health promotion interventions
18 taking place at the crossroad of the organic interiority of the body and the socio-material
19 configurations of its environments. Thus, the permeability of the body to its *milieu* is, for 19th
20 century hygienists, not only a theorization of the chemical relationship between the organic
21 interiority of the former and the chemical activity of the latter. Rather, it constitutes also the
22 fundamental ground for institutional, administrative and political actions directed at governing
23 such bio-social nexus.

24 *1.2 Metaphorical conjectures about ‘organic memory’*

25 The question of heredity became a central issue of biological theories in the middle of the 19th
26 century.⁵¹ Besides the confrontations between Lamarckism and Darwinism, this epoch witnessed
27 a density and proliferation of positions, arguments and experimental practices, which resulted in
28 numerous conceptions of heredity. Such debates straddled the biological and social conceptions
29 of the term, and constituted a prolific epistemic space in which “taxonomies, [...] arguments,
30 [...] architectures of hereditary knowledge, and the conjunctions of these elements” started to
31 circulate in a variety of social arenas.⁵² In order to navigate such space, the monumental work of
32 the French zoologist Yves Delage (1854-1920) constitutes a remarkable milestone. In “*La structure*

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1 In order to account for the physicochemical articulation between acquisition, memory and
2 transmission, Haeckel coined the term 'Plastiden' from the abovementioned Greek *plastos*
3 (molded, formed). The Plastiden designated single-cell organisms, creatures of the lowest
4 morphological or physiological order of "individual." Haeckel imagined these Plastiden to be
5 filled with a substance he called 'Plasson' which in turn was composed of molecules called
6 'Plastidules,' a contraction between 'Plastid' and 'Molecule' that, he argued, "must be considered
7 as the molecular factors of the biogenetic process."⁵⁸ It is not surprising that this ontological
8 invention has been interpreted as an anticipation of DNA.⁵⁹ Yet, it is important to nuance this
9 rapid and teleological interpretation. Haeckel's originality lies less in having imagined a
10 physicochemical substrate of the phenomenon of transmission of characters – many others did
11 that, as Delage testifies – than having tried to integrate into his theory the contextual
12 modifications (or molding) of the very material substrate of life. Haeckel called this process the
13 "perigenesis of plastidules." A detailed explanation of its workings can be found in the legend of
14 his fascinating scheme (Figure 2).

15 [Insert Figure 2 around here]

16 According to Haeckel, the adaptation of plastidules to external influences and the transmission of
17 the transformations induced by these influences can be explained by the same "plastic activity."⁶⁰
18 The plastidules were understood mechanically as being subjected to "a ramified undulating
19 movement, which propagates itself without interruption and that can be considered as the
20 efficient cause of the biogenetic process."⁶¹ Notably, the temporalities of this process do not
21 belong alternatively here to heredity, or contextual (phenotypic) adaptations. The modifications
22 of the plastidular movement make it possible to account both for phenomena of contextual
23 adaptation (i.e. modifications of the plastidular movement acquired during the life-course, which
24 are potentially transmitted to future generations) and heredity (i.e. the accurate reproduction of
25 the plastidular movement from one generation to another). Indeed, this unified biogenetic
26 process is the core of his theory of organic memory: "heredity is the *memory* of plastidules;"
27 variability is instead "the receptiveness" (i.e. the *mnemonic capacity*) of the plastidules. "The former
28 produces stability, the latter variation of organised forms."⁶²

29 Yet, Haeckel's theory also goes further in that it complements this view with a second hypothesis
30 aimed at explaining another fundamental unity in the phenomenon of (human) life. The
31 undulating movement of plastidules is not just a common explanation for ontogenetic and
32 phylogenetic processes but also a heuristic for the continuity between the organic and the

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1 inorganic, the biological and the psychological.⁶³ While at a molecular level the biogenetic process
2 is characterized by the attraction and repulsion of the atoms composing it, at the level of psychic
3 faculties this very same movement manifests itself as "ordinary acts of human intelligence"⁶⁴ or
4 (we would say) sociality. Haeckel's theory affirms, in other words, a monist understanding of the
5 biological and the psychosocial aspects of life, which postulates an additive and progressive
6 continuity (both at the ontogenetic and phylogenetic level) between the basic functioning of life
7 and those of a society. On the one hand, Haeckel affirms that instincts and social attitudes can be
8 explained as manifestations of a faculty progressively accumulated through adaptation, and
9 transmitted through heredity across species: "*animal instincts are no more an exclusive property of animal*
10 *brain than reason is a special privilege of humans.*"⁶⁵ On the other hand, his theory postulates a
11 fundamental ontological unity of phenomena alternatively characterized, in present terms, as
12 social or biological. Indeed, he argues, much as our social existence recapitulates the principles
13 organizing our biology, the cells in our bodies can also be regarded as members of an organized
14 society – a "cellular republic"⁶⁶ – which is affected and shaped "by education, by exercise, by
15 habits."⁶⁷ It is also "the history of human civilization," he concludes, that "explains the history of
16 the organization of multicellular organisms."⁶⁸

17 Haeckel's theory of organic memory provides two conceptual elements that respectively mark a
18 departure from the hygienist paradigm in the diachronia of plasticity thinking, and highlight
19 another way of problematizing the entanglement of biological and social dimensions of (human)
20 life. On the one hand, his ideas account for the articulation between contextual adaptations, their
21 memorization in the atomic structures of plastidules, and their intergenerational transmission.
22 The theory of the 'perigenesis of plastidules' constitutes a different way of conceiving and
23 operationalizing plasticity in that it provides a complementarist view of generation and
24 transmission, variation and stability, adaptation and heredity. Taken at face value,⁶⁹ Haeckel's
25 theory is capable of reconciling the alleged oppositions between Lamarckian and Darwinian
26 theories of evolution.⁷⁰ On the other hand, Haeckel's theory affirms also a fundamentally monist
27 view of the psychological, social and biological aspects of (human) life. This bio-psycho-social
28 hybridity is made possible through the recognition of a common ontology – i.e. the undulating
29 movement of the plastidules – governing life as both a state of conscience, individual experience
30 or social condition and organic process of memorization and reproduction of forms in ontogeny
31 and phylogeny. One inevitable consequence of Haeckel's theory of organic memory is thus that
32 the monism he defended was not merely a biological thesis rooted in expert culture, but rather
33 constituted the ground for broader social, political and lay culture endeavors. For instance, his

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1 drawings of developmental processes exerted a significant influence that goes beyond the field of
2 embryology throughout the 20th century. Haeckel's artistic inclinations inspired views – and
3 attracted several criticisms – regarding the notions of history, evolution and progress they
4 entailed.⁷¹ At a political level, both reactionary and progressive thinker justified in fact distinct
5 options of social engineering on the basis of his representations of ontogeny and phylogeny,
6 which focused respectively on the degenerative effects of social conditions and the social
7 environment as domain of intervention for regeneration.⁷²

8 *1.3 The experimental decoupling of ontogenetic and phylogenetic plasticity*

9 Towards the end of the 19th century, Haeckel's articulation of the relationships among adaptation,
10 memory and heredity is fundamentally challenged. The decisive factor in establishing a divide
11 between plasticity in adaptation and heredity later became known as 'Weismannism,' or – as the
12 author himself calls it – the 'doctrine of the continuity of the germ-plasm.' In commencing his
13 second essay⁷³ aimed at a foundational work for a theory of heredity, August Weismann (1834–
14 1914) affirms that:

15 When we see that, in the higher organisms, the smallest structural details, and the most minute
16 peculiarities of bodily and mental disposition, are transmitted from one generation to another [...] we
17 very naturally ask for the causes of such a striking phenomenon [...]. And the immediate answer to
18 such a question must be given in the following terms: A single cell out of the millions of diversely
19 differentiated cells which compose the body, becomes specialized as a sexual cell; it is thrown off
20 from the organism and is capable of reproducing all the peculiarities of the parent body in the new
21 individual [...].⁷⁴

22 The doctrine rests upon the idea that heredity entails the transfer of a cell (i.e. the germ-cell),
23 which divides early on during development from those constituting the body (i.e. the soma) and
24 that possesses the capacity to develop into a full-blown organism after reproduction. His doctrine
25 was grounded on the conviction that somatic differentiation entailed a progressive loss in the
26 contents of the nuclei (i.e. the germ-plasm – another notion sharing the same etymology of
27 plasticity). This progressive loss of determinants favored the specialization of a given cell (i.e. the
28 expression of cellular specificities) in a given tissue. Consequently, as the complexity of the germ-
29 plasm "gradually diminish[es] during ontogeny," the doctrine had to entail an early segregation of
30 the germ-line from the somatic track.⁷⁵ This was in fact the only way to preserve the full span of
31 determinants from one generation to the other.

32 The separation between the germ and the soma was, however, in direct contradiction with those
33 theories (among which figure prominently Haeckel's perigenesis and Darwin's pangenesis)
34 holding the possibility of some inheritance of acquired characters via the progressive
35 accumulation of somatic modifications transmitted to reproductive cells.⁷⁶ Weismann had

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1 therefore the problem of reconciling continuity and variation with the proposed segregation of
2 the germ line from the soma. He tried to solve it by, first, making a distinction between germ *cells*
3 (i.e. sperm and oocytes in sexually reproducing species) and germ *plasm* (i.e. the material content
4 of germ cells from which an individual develops). This way, he could combine the ideas that the
5 continuity across generations lies in the "substance of the germ-cells, or germ-plasm," and not in
6 the immutability of germ cells, "for the germ-cells are contained in the organism, and the external
7 influences which affect them are intimately connected with the state of the organism."⁷⁷ Second,
8 in a later stage of his work he admitted variations taking place in the germ-plasm itself⁷⁸ by means
9 of external influences upon the development of the germ line and through recombination during
10 fertilization. He was in fact aware of the fact that gametogenesis entailed the loss of part of
11 determinants – what we would call today the transition from a diploid to a haploid genome.⁷⁹

12 Weismann's work was very influential in exposing some foundational limitations of theories
13 linking phenotypic and evolutionary plasticity such as Lamarckism. In order to craft his own
14 theory of heredity, he dedicated a considerable effort to discussing, experimenting with and
15 demonstrating the weaknesses of the available evidence for the transmission of acquired
16 characters. However, his critique was directed at those cases of mutilations or wounds occurring
17 during the lifetime of a parent supposedly transmitted to the progeny, such as the influential
18 experiments conducted on guinea pigs by Charles-Édouard Brown-Sequard.⁸⁰ These cases were
19 problematic to him in that they entailed a modification passing from the somatic to the germ line;
20 that is, they were in open contradiction with his experiments corroborating the early
21 developmental segregation of the latter from the former. So, even though he excluded the
22 "erroneous [...] hypothesis which assumes that somatic nucleoplasm may be transformed into
23 germ-plasm,"⁸¹ nothing prevented him from holding the idea that modifications could occur in
24 the germ-line track. In fact, as mentioned above, he also made clear in later writing⁸² that germ
25 cells – in their own distinct development – may be subjected to modifications from the
26 surrounding environment, which could produce modifications of the elements of the germ-plasm
27 going down the phylogenetic lineage.

28 The appearance of Weismann's doctrine marks therefore a further moment in the recent history
29 of plasticity thinking, which consists of a substantive distinction on experimental grounds
30 between ontogeny and phylogeny. After Weismann, variation and stability in the germ-line
31 require being studied in their own distinguished biological trajectory from ontogenetic processes.
32 Weismann's ideas on the continuity of the germ-line were thus much less conclusive than they

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1 are usually portrayed by the familiar version that constituted 'Weismannism' throughout the 20th
2 century.⁸³ His idea of an early separation between the soma and the germ was less monolithic
3 than it appears in later readings of his work. Weismann himself, in other words, "was not a
4 Weismannian."⁸⁴ The idea he found in need of experimental support within "the animal
5 kingdom"⁸⁵ was the one according to which the progressive losses of determinants from the
6 nucleoplasm (i.e. the content of the nucleus) of somatic cells (which was conditional to cellular
7 specification in his view) could account for the complete restoration of the germ-plasm in the
8 germ cells. Contrary to what later became "a dogmatic faith in Weismannism"⁸⁶ his target was the
9 missing *mechanistic and experimental* explanation that the smallest molecules of heredity can be
10 modified by external influences on somatic cells.

11 Weismann's doctrine is a case worth investigating also for the purpose of our inquiry into the
12 ways plasticity thinking produced specific views of the entanglement between the biological and
13 the social aspects of (human) life. As argued by Meloni,⁸⁷ Weismann's work entails a radical shift
14 in the study of the interactions between experiences, social conditions and the organic
15 functioning of the body. After Weismann, it becomes possible to claim heredity as a biological
16 phenomenon sharply distinguished and separated from social transmission and influences. His
17 doctrine of the continuity of the germ plasm is, for instance, at the origin of the distinction
18 commonly held in psychological and behavioral sciences between innate and learned behaviors.⁸⁸
19 Although such a dichotomy has been largely criticized, one of the essential foundations for the
20 modern study of behavior – as an innate biologically driven character or as a learned, cultural
21 phenomenon – resides in Weismann's germ-plasm theory. Furthermore, and besides his ideas, his
22 graphic representations of differentiation processes have also had a major influence on 20th
23 century's understandings and representations of the separation between social and biological
24 processes.⁸⁹ Weismann's iconographic choice of describing differentiation through cell trees
25 assigned a confined meaning to developmental processes: differentiation takes place through
26 unidirectional relationships, which are not open to effects or feedbacks coming from external
27 agent as well as from lateral processes of differentiation happening across distinct branches.⁹⁰
28 These powerful symbolic and theoretical implications of Weismannism suggest a specific origin
29 of the epistemic separation between studies of our social belongings and the biological aspects of
30 (human) life. The transformations of a society embodied into organic functionings and their
31 implications for heredity are, starting from Weismann, two distinct processes that belong to
32 different disciplinary specialties. By doing so, his work inaugurates what Meloni calls "the
33 transcendence"⁹¹ of the social from its relationship with the organic matter of life. This

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1 separation, we might add, should also be highlighted as the necessary premise for the biosocial
2 reunification of our biological and social existence promised by contemporary epigenetics.

3 *1.4 Plasticity without (environmental) molding of the substance of heredity*

4 The 1930s and 40s witnessed a renewed interest in the relationship between phenotypes induced
5 by the environment and biological inheritance, thus inaugurating a different interpretation of
6 plasticity in the agenda of biology. As shown by Peterson,⁹² an organicist 'third way' of biological
7 thinking proliferated across this period, which marked a departure from the alternative between
8 mechanistic and vitalist understandings of life. In the face of such long-standing dichotomy
9 between life-as-complex-machine and life-as-irreducible-to-molecules, thinkers of such a third
10 way brought to the fore the importance to expand the language of biology beyond the nascent
11 centrality of genes in different socio-political contexts.⁹³ By opening the black box of genotype-
12 to-phenotype transitions and pointing to development as a key process in evolution, these
13 scientists attempted to reconcile the novel episteme of genetics with a complex understanding of
14 organisms, their environments and their mutual interactions. Chiefly, this was the case of Conrad
15 Hal Waddington (1905-1975).⁹⁴

16 Waddington's famous epigenetic landscape⁹⁵ is a "representation of development as a system,
17 whose parameters are genetic loci and whose state space is a set of phenotypic states."⁹⁶
18 Developmental processes are represented in Waddington's landscape as a ball rolling down the
19 landscape whose trajectory is influenced by the (genetically determined) shape of the cliff. It is
20 thus the whole conformation of the landscape (*qua* developmental system) and not any single
21 element (i.e. any single gene) giving it shape, which is at the basis of a phenotypic change. This is
22 illustrated in the less popular "underside of the epigenetic surface" (Figure 3).

23 [Insert Figure 3 around here]

24 Waddington's view of genetic plasticity consists of the capacity of a complex system not to be
25 affected by change in any of its single genetic components. Under this interpretation, plasticity is
26 rather a property of the structure of the system itself. This is the basis of his concept of
27 'canalisation;' namely, the capacity of the genome to attain a given developmental outcome in
28 light of environmental as well as genetic perturbations. Here, again, the author mobilizes the
29 model of the landscape to illustrate this concept:

30 [...] the model immediately suggests that one ought to consider the degree of *canalisation* of any
31 particular path of development. Has the valley a flat bottom and gently sloping sides? If so, there will
32 be only rather a slight tendency for a developmental trajectory, when displaced from the valley centre,
33 to find its way back there again; [...]. On the other hand, if the valley bottom is very narrow and the

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1 sides steep, it will be more difficult to push the trajectory away from its normal course and it will
2 quickly return there.⁹⁷

3 Waddington was not only convinced that canalization could explain phenotypic development,
4 but he argued also for its evolutionary potential: adaptive reaction to "unusual circumstances"
5 may in fact cause an "adaptive character [to become] so far canalised that it continue[s] to appear
6 even when the conditions [return] to the previous norm."⁹⁸ In the paper just cited – published
7 under the suggestive title "Genetic Assimilation of an Acquired Character" – Waddington
8 reported the data from a study he conducted in *Drosophila melanogaster*. The results of this paper
9 display what he calls genetic assimilation; namely, the process through which an *acquired* character
10 (i.e. a variation acquired during one's lifetime) could become an *inherited* one (i.e. a fixed,
11 genetically assimilated variation). The experiment went as follows. After the administration of a
12 heat shock to the pupae of a wild Edinburgh strain of fruit flies, a number of crossveinless
13 specimens appeared with a certain variation, which were classified according to grades of
14 'crossveinlessness' based on the disturbances observed in the formation of the crossveins. Two
15 lines of selection were put in place: upward selection in which only crossveinless flies were bred,
16 and downward selection which encompassed only flies still showing normal wings. After a
17 further selection to reduce genetic variability among the bred flies, the results obtained by
18 Waddington were that flies from the upward selected line started to display crossveinless wings
19 even in the absence of the heat shock.

20 Yet, Waddington did not interpret these results as supporting any form of neo-Lamarckian
21 adaptation.⁹⁹ Indeed, and contrary to what some of his contemporaries believed,¹⁰⁰ his reading of
22 the data can be thoroughly inscribed within a neo-Darwinian framework. His interpretation of
23 these experiments was that the response to the stimulus observed was due to selection occurring
24 at the level of the allelic variants present in the population under study. Simply put, selection in
25 the upward line acted on the distribution of those alleles coding for the crossveinless phenotype
26 raising them up beyond a threshold of frequency allowing the rest of the genome to code for
27 normal wings. As argued by theoretical biologists Eva Jablonka and Marion Lamb:

28 In more modern terms we would say that the variations being selected were the result of different
29 combinations of the alleles of the many genes that are involved in the regulation of development; as a
30 result of selection, the frequency of the initially rare combinations that contribute to an enhanced
31 response to the stimulus increased. Eventually, selection resulted in the production of those originally
32 extremely rare combinations that produce the crossveinless phenotype even in the absence of the
33 temperature stimulus.¹⁰¹

34 However, Waddington's attempt to reconcile the hypothesis of acquired characters with one of
35 the main pillars of the Modern Synthesis (i.e. that Darwinian natural selection acts upon variation

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1 of Mendelian genes) had little influence (at least in genetics) for several decades.¹⁰² As the
2 Synthesis evolved "toward a conservative centre, with little room for more creative and complex
3 ideas,"¹⁰³ his views were received as a revival of Lamarckism, now viewed as a threat for both
4 theoretical and political reasons. At a theoretical level, his interpretation of the crossveinless flies
5 experiment was at odds with the genetic preformationism to which many of his contemporaries
6 adhered. His view that genes do not define the emergence of a trait – but rather represent a set of
7 potentialities to be alternatively transformed into different phenotypes depending on
8 developmental conditions – had a Lamarckian flavor that contrasted with the received
9 deterministic view of genotype-to-phenotype transitions.¹⁰⁴ At a political level, explaining the
10 demise of Waddington's plasticity thinking requires taking into account the rise of Lysenkoism in
11 the Soviet Union and the "morality tale" associated with such a research program in the Western
12 genetics community of the early Cold War years. The political plot orchestrated by Lysenko –
13 that led to the death of his adversary Nikolai I. Vavilov – was soon deployed as an argument
14 against both the ideas (i.e. environmental determination of variation and inheritance of acquired
15 characters) and the views on the governance of science (e.g. the centralized planning of science)
16 associated to the Soviet scientist. In such a political atmosphere, Waddington's alleged
17 Lamarckism, coupled with his left-wing political leanings,¹⁰⁵ displayed a damning resemblance to
18 the aberrations of Lysenkoism, which negatively affected the reception of his work in genetics
19 circles.¹⁰⁶

20 Nonetheless, his contribution can be regarded as yet another key moment in the recent history of
21 plasticity thinking. Even though the outcome of his experiments was the inheritance of acquired
22 characters, his ideas about the genome do not require such inheritance to generate any
23 modification of the fundamental substance of life. While the organic memory of Haeckel, and the
24 modifications of the germ-plasm evoked by Weismann all conceive plasticity as material
25 inscription of the environment into life's determinants, in Waddington's work these
26 modifications are located in a different theoretical space. Plasticity is here a property emerging
27 from gene expression in ontogeny and from gene selection in phylogeny. Otherwise stated,
28 plasticity in Waddington is the attribute of a complex system whose responses to perturbations
29 do not require the material molding of the fundamental substance of heredity. Rather, adaptation
30 and variation emerge here from a (developmental) process actualizing the several potentialities of
31 a complex genetic machinery capable of responding to perturbations in its components and/or
32 its environments, and of evolving across the temporalities of natural selection.

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1 Furthermore, it is worth noting how Waddington's operationalization of plasticity constitutes a
2 distinct theorization of the relationship between life as biological and social phenomenon. His
3 polemical stance towards the Modern Synthesis was in fact not only dictated by a fundamental
4 disagreement around the deterministic model defended by his "preformationist" colleagues.
5 Rather, his theory of epigenesis was part of a larger philosophical project aimed at demolishing
6 the "Bifurcation of Nature,"¹⁰⁷ as stated in the motto of the Whiteheadian organic philosophy to
7 which he subscribed.¹⁰⁸ Waddington considered untenable a dualism of matter that considered
8 the organism and its environment, the biological and the psychological, the mind and the body as
9 entities characterized by distinct ontologies. The tenets of his organic philosophy constituted a
10 'scientific attitude'¹⁰⁹ towards complexity that went beyond the understanding and representations
11 of our biology. As argued by Susan Merrill Squier,¹¹⁰ several of his writings and professional
12 engagements consisted in an attempt to provide a unified theory of complexity useful to biology,
13 philosophy and the arts alike. His metaphor of the landscape, the author shows, has had an
14 immense impact beyond the borders of the life sciences reaching out into modern art, popular
15 scientific representations as well as landscape architecture. Waddington analogical model
16 provided a heuristics to conceptualize systems like biological ones, but also human societies. As
17 he points out, his organic thinking applies as well to the analysis of totalitarian political regimes,
18 or the scrutiny of social systems as "integrated wholes" whose good depends on "the good of its
19 individual members."¹¹¹ In its wide-ranging – and often unfulfilled – ambitions¹¹², Waddington's
20 organicism was thus a manifesto of scientific humanism calling for the reunification of what he
21 ironically called "prim Science" and "harlot Humanities."¹¹³ In this respect, Waddington's ideas
22 provide us with another instance of the ways plasticity thinking in the life sciences also opened
23 avenues for interrogating the relationship between life as biological and social phenomenon. His
24 organic philosophy may be regarded as an *ante litteram* precedent to the contemporary quest for
25 integrative biosocial approaches to the study of health and disease that could move us beyond
26 irreducible oppositions between the social and life sciences.

27 **Part 2 – The synchronic dimension: 'plasticity' in contemporary epigenetics**

28 So far, we have identified four distinct conceptualizations and operationalizations of plasticity
29 across the 19th and 20th centuries. First, we have witnessed the appearance of a paradigm of
30 *chemical modification of the body* in the case of 19th century French hygienists. According to them,
31 health and disease must be understood as deviations from a normal state caused by the porosity
32 of the inner functionings of our bodies to a given (chemical, social and political) *milieu*. Second, in

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1 the examination of theories of organic memory, and most notably Haeckel's perigenesis of the
2 plastidule, we could identify uses of plasticity as *explanandum for the modifications of life substrates* in
3 development and evolution. Plasticity here accounts for the reproduction of species-specific traits
4 as well as adaptations with evolutionary impact. Third, in the analysis of Weismann's doctrine of
5 the continuity of the germ-plasm, we have seen how a fundamental distinction was put in place at
6 the end of the 19th century between changes happening at the somatic level and those affecting
7 the germinal lineage. Weismann's views, we showed, were less doctrinal than it has often been
8 assumed and moved the understanding of plasticity from the process of molding the vital
9 substratum (in both ontogeny and phylogeny) to *a mechanistic process in need of explanation*. Fourth, in
10 the case of Waddington's notions of 'canalization' and 'genetic assimilation,' we observed how
11 plasticity became the property of a developmental system that is capable of processing
12 environmental signals and is governed by the laws of natural selection. According to
13 Waddington, plasticity has to be understood as *responsive potential* of the genome to resist
14 perturbations.

15 In this section, we turn these four historically-situated understandings of plasticity into an
16 analytical grid to distinguish distinct epistemic approaches to body-environment relationships,
17 development and inheritance in contemporary epigenetics. The history of 20th century epigenetics
18 consists of a number of cognate endeavors that, while affirming a common affiliation to
19 Waddington, often pursue research programs that stand in open contrast with one another.¹¹⁴ A
20 uniform characterization of the fundamental epistemological tenets of this scientific field is a
21 hard task,¹¹⁵ and also representations of epigenetics in public discourses are often fragmented or
22 contradictory. Recognizing that historical work on epigenetics could illuminate its plural
23 epistemologies,¹¹⁶ in this section we describe few discrete understandings of plasticity across
24 various sub-fields of epigenetics such as epigenomics, behavioral/environmental epigenetics, and
25 epigenetic epidemiology/exposomics. Our analysis does not aim to systematically classify all
26 distinct usages of plasticity in contemporary epigenetics, but rather to provide a few situated
27 examples of how this notion entertains distinct theoretical stances and experimental practices
28 within this domain. As we shall see, the four distinct historically-situated understandings of
29 plasticity we isolated above can be helpful to characterize and distinguish the diverse explanatory
30 functions of this notion in contemporary epigenetics.

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1 2.1 *Plasticity in epigenomics*

2 A substantial part of research funding in epigenetics currently falls under the label of
3 'epigenomics', which exploits the power of next-generation sequencing to map the epigenetic
4 patterns (i.e. epigenomes) characterizing the diverse tissue types in our bodies. Reference human
5 epigenomic maps are currently a free resource available to researchers interested in the study and
6 comparison of the epigenetic differences that characterize hundreds of cell types in a 'normal' or
7 'aberrant' state.¹¹⁷ A closer look at these maps reveals that this strand of epigenetic research
8 employs and operationalizes an understanding of plasticity as the capacity of the genome to
9 produce a diverse range of phenotypes. The epigenome is here characterized as a series of steady
10 state conformations of the genome that are specific to distinct types of cells in the body, and to
11 the transitions between health and disease in a given tissue. In its current and most advanced
12 formulation, epigenomic data are a multi-layered description of the "epigenetic plasticity that
13 enables cells to undergo [a] wide range of [cellular] lineage specifications."¹¹⁸ From chemical
14 modifications of DNA not affecting the sequence (e.g. methylation), to modifications of the
15 proteins around which DNA is compacted into chromatin (e.g. histone modifications), up to
16 higher-level reshufflings of nuclear architecture, epigenomic maps integrate different snapshots
17 of the material operators of regulation and expression of the genome in a complex
18 representation. Plasticity in epigenomics is thus a distinctive *combinatorial* notion; namely, the
19 result of distinct layers of genomic activity acting in concert to determine complex phenotypes,
20 specifications, and transitions in the cells of our bodies. The different material operators of
21 genomic differentiation (e.g. methylation, histone modifications, nucleosome positioning) build
22 upon and extend the information potential of DNA in order to craft the diverse phenotypic
23 characteristics of each cell type. The epigenetic profile of any given cell is in fact the result of
24 programmed DNA arrangements, which unfold into the material structuring of distinct layers of
25 combinations among DNA, RNAs, histones, and chromatin modifications in the nuclear genome
26 of a cell.

27 Epigenomic maps permit us to describe a first conceptualization and operationalization of
28 plasticity in contemporary epigenetics. Our genome is here regarded as a developmental resource,
29 which possesses the capacity to unfold into various epigenomic potentials – being these the
30 different cell types of the body, or the molecular configurations of a diseased tissue. In this
31 respect, plasticity in epigenomics is continuous with the intellectual program of authors such as
32 Waddington.¹¹⁹ At the same time, the idea of genetic control of phenotypic plasticity in

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1 epigenomics appears to be imbued also with Weismannism as interpreted by the 'central dogma'
2 of molecular biology.¹²⁰ Respectively, epigenomics goes along the same track of plasticity thinking
3 *à la* Waddington in that it postulates the differentiation from the zygote to the whole range of
4 tissues in our body (both healthy and diseased) to be captured by a panoply of steady-state
5 cartographies of the (normal or pathological) epigenetic signatures of each different cell type. In
6 short, epigenomic maps describe, in a Waddingtonian fashion, the behavior of the genome as a
7 complex developmental system crafting a given phenotype. At the same time, epigenomic
8 scientists provide an understanding of plasticity which is essentially (i) on the side of the soma by
9 the standard of Weismann's barrier, and (ii) an intrinsic genetic property that flows from DNA to
10 combinations of gene expression, conformations of regulatory regions and genomic architectures
11 of cells. In fact, plasticity is here on the side of soma because epigenomics postulates that cellular
12 differentiation belongs to phenotypic development and does not contribute to modifications of
13 the fundamental substance of heredity. In line with the 'doctrine of the continuity of the germ-
14 plasm', plasticity in epigenomics is postulated as a transfer of sequential information between
15 levels of genomic regulation, which does not involve any transmission of acquired information
16 across the germ line. Furthermore, the interpretation of plasticity in epigenomics is also deeply
17 imbued with the paradigm inaugurated by classical quantitative genetics as it postulates that
18 genetic variations are the main material operator of cellular differentiations from healthy to
19 diseased states. State of the art epigenomic maps take in fact genetic variation both as a
20 'difference maker'¹²¹ of the transition from normal to aberrant epigenomic states, and as the 'trait
21 maker'¹²² constituting the epigenetic profile that characterizes the phenotype of a given tissue. It
22 is quite telling, in this respect, that the word 'plasticity' occurs in the special issue of *Nature*
23 comprising the first hundreds of epigenomic maps only in two specific contexts. Firstly, in
24 relation to the effects of genetic variation on the architectural arrangements of chromatin,¹²³ and
25 secondly in the context of the quantitative analysis of downregulated genes for "synaptic
26 plasticity" in Alzheimer's disease.¹²⁴

27 *2.2 Plasticity in behavioral and environmental epigenetics*

28 Researchers in fields such as 'behavioral epigenetics' and 'environmental epigenetics' address the
29 question of plasticity as "signals from the environment" that "trigger molecular biological
30 changes."¹²⁵ Differently from epigenomic maps, these studies have provided an understanding of
31 how exposures to toxic substances¹²⁶ as well as stressful conditions¹²⁷ can trigger germ-line-
32 mediated inheritance of epigenetic predispositions for behavioral patterns or health conditions.

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1 In so doing, behavioral or environmental epigeneticists postulate a very precise role for plasticity,
2 which amounts to the embodiment of environmental conditions in phenotypic development and
3 heredity. These scientists hypothesize that the social environment (especially at early stages of
4 life) has a long-term impact on mental and physical conditions via the imprinting of epigenetic
5 signatures.¹²⁸ The biology of complex traits (e.g. stress-coping, fear, fertility) is to be explained,
6 under this view, by the mutual shaping of genes and their environment (from experiences, to
7 exposures, to genes and back to phenotypes and behaviors).

8 In a remarkable revival of ancient ideas of organic memory, such as Haeckel's theory of the
9 'perigenesis of the plastidule,' these epigenetic scientists advance a programmatic effort to dissect
10 mechanistically how the plasticity of our genome entails environmental modifications of the very
11 substance of development and heredity. As argued by Moshe Szyf, a prominent actor in this field,
12 processes of epigenetic programming triggered by environmental stimuli take place over blurred
13 temporalities of ontogeny and phylogeny:

14 If multigenerational transmission of *ancestral experiential memory* evolved to increase survival and fitness,
15 such a mechanism should be able to modulate phenotypes crucial for survival [...]. It is plausible then
16 that nongenetic inheritance would function at different timescales depending on the nature of the
17 ancestral experience. Maintaining plasticity in response to dynamic environments requires generation-
18 limited and reversible reprogramming. By contrast, a permanent change in habitat requires a stable
19 multi-generational phenotypic transformation.¹²⁹

20 Indeed, behavioral and environmental epigeneticists have even gone further in paralleling
21 Haeckel's ambition to integrate ontogeny and phylogeny, as well as Lamarckian and Darwinian
22 evolution in the conceptualization of their epistemic work.¹³⁰ According to Szyf,¹³¹ the disputed¹³²
23 possibility that environmental exposures could produce transgenerational adaptations via
24 epigenetic programming (in the absence of genetic change) is a vindication of Lamarckism. In his
25 view, the idea of the inheritance of acquired characters has been marginalized due to the lack of a
26 plausible mechanism serving as "conduit between the environment and stable alteration of gene
27 function that could be stably transmitted through the germline."¹³³ Evidence of epigenetic
28 inheritance via the gametes provides such a mechanism, thus suggesting that evolution (in a neo-
29 Darwinian sense) has equipped organisms with "mechanisms to respond specifically and
30 efficiently to certain critical novel experiences," and "to transmit this information effectively to
31 their offspring" without necessarily involving "the typically slow process of natural selection."¹³⁴
32 In a nutshell, the plasticity of epigenetic marks enables the author to argue that Darwinian
33 evolution has crafted at least one mechanism for Lamarckian evolution to occur.

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1 In contrast, another influent environmental epigeneticists such as Michael Skinner argues that
2 environmental epigenetics and transgenerational epigenetic inheritance provide grounds for
3 integrating another "neo-Lamarckian concept"¹³⁵ into the Neo-Darwinian theory of evolution.
4 His ideas build upon the substantial corpus of epigenetic research dissecting the involvement of
5 epigenetic processes in disease aetiology. These studies show how epigenetic mechanisms (most
6 notably, DNA methylation) can promote genomic instability and induce genetic mutations. What
7 emerges then as epi-mutation transmitted to the progeny has, in Skinner's understanding, also a
8 role in producing genetic changes and variations that in turn are subjected to natural selection.
9 This way, the author can claim a dual role for epigenetic processes in evolution: one (that we
10 encountered in Szyf's work) pointing to the transmission of acquired phenotypic characters
11 through germline-mediated epigenetic inheritance. The other, instead, pointing to the role of
12 these epigenetic mechanisms in inducing mutations on which natural selection intervenes
13 subsequently. Briefly put, epigenetics enables the author to postulate that a neo-Lamarckian
14 mechanism could be the driver of neo-Darwinian evolution.

15 Interestingly, neither a direct reference to past theories of organic memory, nor the
16 etymologically dense terminology of Haeckelian heritage can be found in the academic
17 production of these authors¹³⁶. Both authors inscribe instead their views as standing in continuity
18 with those of Waddington, who is acknowledged in their writing not just as the originator of the
19 field of epigenetics, but as a forerunner of studies of plasticity as mechanism of non-genetic
20 inheritance¹³⁷. The word 'plasticity' is explicitly problematized in only one of the texts analyzed
21 above¹³⁸, although it occurs extensively elsewhere in these scientists' production,¹³⁹ and it is often
22 equated with "epigenetic alterations"¹⁴⁰ and "molecular mechanisms"¹⁴¹ for the influence of the
23 environment on inherited biological traits. We thus see at play here how the epistemic space¹⁴² of
24 contemporary epigenetics harbors distinct and often unacknowledged traditions of plasticity.
25 While scientists' narratives of the field and its epistemological foundations refer to Waddington
26 to reinforce the idea of a common origin of its different epistemic programs, a thorough scrutiny
27 of the conceptualizations and operationalizations of plasticity in this field suggests a different
28 reading. Drawing from the four distinct historically-situated understandings of plasticity we
29 isolated above, it is in fact possible to characterize how this notion instructs distinct conceptual
30 and experimental endeavors across different corners of epigenetics. At a closer look, plasticity in
31 environmental and behavioral epigenetics seems to have little in common with the way this
32 notion was conceptualized and experimented with in Waddington's work, or the way it is
33 currently being interpreted in the field of epigenomics. Rather, plasticity seems to be bestowed

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1 here with the capacity to account for the very same molding of the fundamental substance of
2 heredity, which was a fundamental facet of its interpretation in Haeckel and that is still required –
3 in these authors' view – to explain a common biological basis for ontogeny and phylogeny.

4 *2.3 Plasticity in molecular epidemiology and exposomics*

5 A similar style of reasoning informs those research designs currently encompassed by the labels
6 of 'molecular epidemiology' or 'epigenetic epidemiology.' These approaches – “marrying a bench
7 science and a population science” – aim at identifying the “mechanistic link between
8 environmental exposures and diseases outcomes.”¹⁴³ Some molecular epidemiologists adopt a
9 life-course perspective to address questions regarding the relationship between socio-economic
10 status and epigenetic biomarkers for susceptibility to disease.¹⁴⁴ Some others focus instead on
11 development and highlight the importance of epigenetics to understand early-life exposures
12 leading to adult diseases under the overarching hypothesis of the “Developmental origins of
13 health and disease–DOHaD.”¹⁴⁵

14 During the critical periods of ontogenesis, [environmental] influences result in modifications
15 connected with *ontogenetic plasticity* that lead to permanent changes in structure and function of
16 different organs and systems of an organism.¹⁴⁶

17 Among the various ways of experimenting with body-environment plasticity and permeability in
18 molecular epidemiology, the concept of 'exposome' has been recently gaining traction.¹⁴⁷ The
19 exposome heralds a turn in the relationship between epidemiological sciences and molecular
20 biology. First, exposomics widens the breadth of molecular approaches in epidemiology by
21 postulating different levels of genomic regulation and expression (e.g. metabolomics, proteomics)
22 beyond the epigenome as concurring “biosensor[s]” that modulate body-environment
23 interactions and “hence trigger disease.”¹⁴⁸ Second, exposomics opens up molecular epidemiology
24 to a detailed characterization of the chemical interactions between the body and its surrounding
25 material and social environments.¹⁴⁹ The exposome is supposed to counter a strict focus on
26 genomic plasticity as the main *explanandum* of disease aetiology through the association of genetic
27 variants with health outcomes in the population.¹⁵⁰ The problem with these studies, according to
28 exposomic scientists, is a consideration of disease causation as a genetic phenomenon. This
29 approach, they argue, proved unable to explain how diseases develop given the prominent role of
30 environmental exposures in producing a given phenotype. For this reason, exposomic studies
31 revolve around a measurement of the entire set of exposures to which individuals are subjected
32 from conception onwards throughout their lifespan.¹⁵¹ Such a concept stresses therefore the
33 importance of measuring the environment in its totality (from environmental pollutants to work-

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1 related exposures and lifestyles over the life-course) and to complement this measurement of the
2 "external" environment with a characterization of the "internal chemical environment" where the
3 external environment gets processed into the metabolic functioning of the body.¹⁵² Thus, the
4 exposome is conceived as an epistemic tool describing the biochemical processes linking the
5 body with its surroundings, the genomic predispositions with the "endogenous and exogenous
6 chemicals in the body at [any] given time."¹⁵³ Researchers in this field stress the need to combine
7 knowledge from classical epidemiological methods (e.g. exposure matrices, dietary recalls) with a
8 characterization of 'downstream' biological events such as analyses of the chemical compounds
9 circulating in bodily fluids (e.g. blood¹⁵⁴), or the modifications of gene expression brought about
10 by epigenetic changes.¹⁵⁵ The complementarist view of exposomic studies is that the role of the
11 environment in disease development should be reduced neither to a disturbance of a genetically-
12 driven process (like in epigenomics) nor to the effects of one exposure (like in behavioral or
13 environmental epigenetics). Rather, exposomics encourages taking the plastic cross-talk between
14 environments and the genome – the "molecular conduit" between the inner and the outer¹⁵⁶ – as
15 a whole, multi-layered biochemical process by which the environment enters the body.

16 As illustrated by a recent and influential issue of the *International Journal of Epidemiology (IJE)*,
17 scientists across these various strands of molecular epidemiology (re)construct the history of their
18 field against the backdrop of Waddington's work. The issue revolves around a reprint of
19 Waddington's 1943 paper 'The Epigenotype' and is presented as both a celebration of the
20 importance of his ideas for the field and an overview of the various approaches that follow his
21 ideas in epidemiology. Besides the reprint of 'The Epigenotype,' the issue includes in fact also: a
22 series of commentaries on the legacy of Waddington's work for epigenetic epidemiology written
23 by renowned evolutionary and theoretical biologists;¹⁵⁷ a number of theoretical and empirical
24 papers that deal with the import of epigenetics for the study of prominent epidemiological
25 questions (e.g. the association between socio-economic status and health inequalities);¹⁵⁸ a review
26 on the translation of exposomic approaches into concrete research programs;¹⁵⁹ as well as a
27 symposium around the book by Patrick Bateson and Peter Gluckman on plasticity thinking in
28 epidemiology across development and evolution.¹⁶⁰ No doubt, conceptualizations of plasticity in
29 molecular epidemiology present several analogies with its Waddingtonian interpretation analyzed
30 above. Like Waddington, these scientists conceive and operationalize biological plasticity as the
31 set of causal mechanisms that intervene between the genotype and the phenotype during the life-
32 course. Furthermore, epigenetic epidemiology views of plasticity are also grounded on an
33 understanding of the genome as dynamic network and resource that crafts the phenotype

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1 through complex processes at the crossroad of gene regulatory networks and environmental
2 conditions.¹⁶¹ Yet, the construction of this historical trajectory from Waddington to present
3 molecular epidemiology also obliterates some major differences between the reflections around
4 plasticity animating this field and those purported by the British biologist. Of note, molecular
5 epidemiologists are only partly concerned with processes of embryogenesis and development as a
6 matter of evolutionary significance. With the exception of some epidemiological approaches
7 grounded on DOHaD hypothesis¹⁶², the majority of scientists in this domain rather focus on the
8 modifications to which individual bodies are subjected from conception to the adult age.
9 Furthermore, Waddington's epigenotype provides only a limited ground to cast developmental
10 processes and complex genotype-to-phenotype transitions as open to environmental stimuli. As
11 acknowledged also by the editorial introducing this special issue of IJE, this particular paper of
12 his "says nothing about environmental modifiers of gene expression."¹⁶³

13 In this respect, the different strands of molecular epidemiology rather evoke the
14 operationalization of plasticity animating the hygienist movement at the beginning of the 19th
15 century.¹⁶⁴ As in the case of early hygienists, these researchers take the environment as a 'plastic
16 life modifier;' namely, a variable that produces a fundamental change in biological functioning
17 and a deviation from the normal to the pathological. Much like their 19th century predecessors,
18 they consider the body as an open metabolic entity penetrated and modified by the external
19 world – incidentally reduced also here to a taxonomy of different types of exposures (see section
20 1.1). Yet, it is worth mentioning how at least one major difference can be found in the
21 articulation of these two historically distant paradigms. While public hygienists black-boxed the
22 inner workings of the reciprocal modulations of bodies and environments, molecular
23 epidemiologists attempt to unfold the fundamental mechanisms of this process thanks to an
24 approach that draws from various facets of contemporary biology. The problem for the French
25 hygienists was in fact less dissecting individual differences in the chemical interactions between
26 bodies and *milieu* than the recognition of a social problem equally affecting every citizen's body as
27 normal metabolic entity. By contrast, contemporary molecular epidemiologists render vivid the
28 chemical continuum in which the body and its inner working stand with respect to the exposures
29 to which it is subjected. In brief, the metabolic body of molecular epidemiology is no longer an
30 organic substrate that is essentially the same for everyone, but rather a multi-layered molecular
31 entity that combines unique genetic and metabolic predispositions with exposures and chemical
32 alterations specific to one's material and social environment.

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1 Discussion. Plasticity, epigenetics and the biosocial.

2 Our historical and epistemological analysis of 'plasticity' illuminates several differences in the
3 general mind-sets and the concrete research accounts mobilizing this notion in contemporary
4 epigenetic biosciences. Current mobilizations of this notion as *explanandum* for phenotypic and
5 (potentially) evolutionary adaptations present several analogies with distinct conceptualizations
6 and operationalizations across the last two centuries. This is not meant to deny that 19th and early
7 20th centuries debates seeking to explain the plastic development and evolution of organic forms
8 have given rise to traditions that strongly contrast with one another.¹⁶⁵ Far from constituting an
9 exhaustive reconstruction of the historical and epistemological complexities of biological thinking
10 in the last two centuries, the different trajectories we drew are meant only to historicize and
11 distinguish the modes of understanding body-environment relationships in contemporary
12 epigenetics. Specifically, drawing these historical parallels can (i) reveal major differences among
13 uses and conceptions of plasticity internal to epigenetic life sciences; (ii) highlight how the
14 fundamental disagreements animating plasticity thinking across the 19th and 20th centuries have
15 persisted until today; and (iii) position the diverse epistemologies of plasticity in epigenetics with
16 respect to the ways this notion enables the production of a biosocial understanding of (human)
17 life.¹⁶⁶

18 First, our work provides several entry points on the diverse explanatory functions that plasticity
19 plays in the synchrony of current epigenetic biosciences. As shown above, researchers from
20 different sub-fields of epigenetics often turn to Waddington to construct themselves as heirs of a
21 past in which the gene was not the sole and ultimate source of biological information.¹⁶⁷ Yet, our
22 analysis demonstrates how variegated is the economy of concepts, causal explanations and
23 experiments afforded by plasticity thinking in contemporary epigenetics. Without the need to
24 read these differences in the present as the actual confrontation among the distant traditions we
25 explored above, our analysis illuminates the epistemological gaps among co-existing views of
26 plasticity in epigenetics.

27 The analogies we drew in our work underline in fact that the controversies internal to the field of
28 epigenetics may be due more to a fundamental *epistemological disagreement* around views of plasticity,
29 than the alleged lack of evidence in support of any of the different approaches populating this
30 field. Clearly, molecular epidemiologists and behavioral/environmental epigeneticists share with
31 their predecessors grappling with hypotheses of 'organic memory' a notion of plasticity
32 committed to an understanding of the molecular patterns that allow the environment to mold the

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1 substance of development and heredity. In so doing, both of these approaches counter the
2 interpretation that is common within epigenomic research. Epigenomic scientists understand
3 instead plasticity as a combinatorial property of genetically-driven networks of development.
4 Thus, while in the former cases plasticity mediates a traffic between the internal and the external
5 and affords a mnemonic capacity of the body, the latter takes the environment as a signal to be
6 processed by a complex genetic system.¹⁶⁸ Hence, within epigenomics, plasticity is the
7 actualization of a systemic potential of the genome to give shape to a phenotype. In
8 behavioral/environmental epigenetics and molecular epidemiology, instead, plasticity stands for
9 the capacity of the genome to be permeable to its environments.¹⁶⁹ Yet, major conceptual
10 differences as to how plasticity should be characterized, understood and mobilized as an
11 experimental resource exist also between these two sub-fields of epigenetic sciences. On the one
12 hand, behavioral and environmental epigeneticists construct a model of a given 'environmental
13 phenomenon' (e.g. pesticide exposure) by specifying thresholds of 'good' or 'bad' stimuli, in
14 order to suggest a causal relationship between such stimuli, an epigenetic state (e.g. the
15 methylation patterns of a certain gene), and a given phenotype (e.g. fertility).¹⁷⁰ Thus, these
16 approaches display an understanding of plasticity as a means by which an external phenomenon
17 (e.g. chemicals, nutrients, stress, etc.) gets materially engraved into our genome through specific
18 molecular mechanisms. On the other hand, molecular epidemiologists – especially in the field of
19 exposomics – multiply the complexity of such "molecular conduit"¹⁷¹ by stratifying the totality of
20 environmental exposures as a cumulative source of causality in life-course health trajectories. In
21 this vein, plasticity is the permeable feature of the body and not simply the mnemonic capacity of
22 the genome; that is, it is the feature of an organic system whose unique inner workings chemically
23 intertwine with those of a neo-hygienist *milieu*.

24 We can thus elaborate here on how our historico-epistemological analysis unveils a fundamental
25 epistemological disagreement around plasticity in contemporary epigenetics. As argued by Ute
26 Deichmann,¹⁷² contemporary epigeneticists part over the interpretation of epigenetic
27 modifications of gene expression. To some, epigenetic changes are the result of modifications
28 mediated by sequence-specific transcription factors. According to this view – predominantly
29 popular among epigenomic scientists – what other epigeneticists ascribe to environmental
30 influences (like in molecular epidemiology), or to an alleged mnemonic capacity of the genome
31 (as in behavioral/environmental epigenetics) is instead due to specificities of the transcriptional
32 machinery and individual DNA sequence variability.¹⁷³ By affecting the accessibility of the
33 genome, genetic factors – and not epigenetic modifications – are the mediators of changes in

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1 gene expression. According to others, the causal primacy between epigenetic and genetic factors
2 has instead to be inverted: regulatory changes stem from the epigenetic modification itself. This
3 view, common in the two camps of molecular epidemiology and behavioral/environmental
4 epigenetics, points instead to the potentially paradigm-shifting aspects of epigenetic findings.
5 Chemical modifications of DNA and its structure are, in this view, an additional layer of
6 information that links the genome to its material and social environments. Otherwise stated,
7 these researchers question the idea of the genome as first cause, and argue against a gene-centric
8 view of development, life-course health trajectories and (potentially) evolution.¹⁷⁴ In fact, another
9 point of controversy relates to the temporal frames in which these modifications are taken to
10 operate. According to some, epigenetic modifications are confined to mitosis; namely, the
11 process of cellular reproduction in development, growth and tissue regeneration. According to
12 others, instead, epigenetic modifications extend beyond cell division to constitute mechanisms of
13 heredity and evolution.¹⁷⁵

14 Most of the definitions of epigenetics today do not distinguish between these different
15 phenomena,¹⁷⁶ thus allowing this plurality of views to thrive under the same ambiguous heading.
16 Concomitantly, however, a strong skepticism about what biological phenomena count as
17 epigenetic ones polarizes the various sides of this controversy. Several actors¹⁷⁷ and
18 commentators¹⁷⁸ in the field invest the need for "hard data" as a potential solution to the
19 reciprocal skepticism that has set among these different approaches in epigenetics. Yet, our
20 analysis suggests that these confrontations rather play out as divergent conceptualizations of
21 plasticity, which have implications for the definition of the scope and epistemic priorities of
22 epigenetics. While cautionary tales about the inconclusive nature of epigenetic studies may serve
23 the aspiration of an all-encompassing definition of the field, our work underlines that hard data
24 may not deliver the synthesis among these divergent views. Quite the contrary, our analysis
25 provides evidence to doubt that conceptions of plasticity holding capable epigenetic marks to
26 bear the material impression of the environment may be reconcilable with those view of this
27 notion that place it under a strict genetic control.

28 Second, our historico-epistemological analysis of plasticity provides a particularly illustrative
29 entry-point to the enduring nature of the economy of concepts, experimental designs, and
30 biological theories animating the field of epigenetics today. Otherwise stated, it details how – as
31 recognized also by others¹⁷⁹ – the cardinal question of how to account for the reciprocal
32 modulation of organic substrates and their contexts of development has persisted throughout

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1 major changes in the scientific concepts and the experimental cultures of biological thinking. This
2 recognition allows us to cast a critical gaze on the supposed novelties attributed to epigenetics.
3 Looking at the recent history of biology through the lens of plasticity indicates that current
4 questions in epigenetics – concerning the role of the environment for development, heredity and
5 evolution – are continuous with the history of biology as a discipline. In this respect, our work
6 calls into question the idea that contemporary biology has moved from gene-centrism towards a
7 more holistic understanding of life.¹⁸⁰ Contrary to this popular reading of epigenetics as the
8 purveyor of a 'revolution' in the life sciences¹⁸¹, our work shows that thinking of the 'gene' as
9 devoid of any interaction with its environments is more a rough simplification of the recent
10 history of biology than a monolithic stance of any recent time in this domain.¹⁸² The 'chemical
11 body' of French public hygienists, the 'plastidule' in Haeckel, the 'germ-plasm' in Weismann, the
12 'genotype' in Waddington – to name the representative few we mobilized – represent several
13 examples of how the life sciences have constantly attempted to come to terms with the multiple,
14 complex and ecological elements of the development of forms of living.

15 Third, this points to a further finding that relates to the biosocial openings offered by
16 contemporary epigenetics. The possibilities epigenetics offers to think about the hybridities
17 between our biological and social existence are at the center of much attention on the part of
18 social scientists.¹⁸³ As we have seen, the heuristic function of plasticity in its diachronic
19 development went beyond a simple attempt to make sense of the reciprocal modulation of
20 organic substrates and their environments in ontogeny and phylogeny. Operationalizations of
21 plasticity thinking in the 19th and 20th centuries constituted also the material and factual resources
22 to imbue knowledge of the body with coeval socio-political contexts. As shown above, plasticity
23 thinking provided a vocabulary of mechanisms, imaginaries and explanations that resonated
24 across social spaces as cultural and symbolic objects. Plasticity thinking testifies, in other words,
25 of different modalities to conceive the processual engagements and social embeddedness of our
26 biology. Within the historical instances we have briefly analyzed, plasticity enabled
27 understandings of social progress, of the unity between biological and social phenomena as well
28 as provided a ground for political action. In brief, a historical epistemology of biological plasticity
29 offers the possibility of identifying traces of biosocial thinking in the past, and raises the question
30 of how these multiple facets of the biosocial are re-interpreted within contemporary debates.
31 As shown by Jorland,¹⁸⁴ the institutionalization of the chemical episteme of 19th century hygiene
32 in France related to a conception of liberal biopolitical action that framed humans as biological
33 and social beings. The hygienist concern with the government of population health thus points to
34 the necessity of investigating contemporary translations of plastic conceptions of the body into

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1 strategies of intervention over the biological and social factors of health and disease.¹⁸⁵ Haeckel's
2 theory of organic memory was concerned – like present debates around the biosocial – with the
3 difficulty to find a common ontology for psychosocial and biological aspects of life. This
4 recognition underlines the need for a critical uptake of the synthesis between the biophysical and
5 sociocultural conceptions of human existence in current post-genomics:¹⁸⁶ what if the ontology of
6 the biosocial emerging from the increasing convergences between social and biological sciences is
7 flattened to the one-category ontology of biochemistry dominating the life sciences? The role of
8 Weismann's experiments in forging a separation of the social from the biological constitutes the
9 necessary premise on which calls for the reunification of social and biological sciences rest in the
10 present of the biosocial age.¹⁸⁷ In doing so, Weismann's work reminds us of the historical
11 sedimentation of the bio-social divide, and of the barriers and difficulties that may be faced in
12 restoring an integrative biosocial epistemic approach. How to avoid the potential
13 molecularization of our social understanding of life that could arise from contemporary biology's
14 style of reasoning?¹⁸⁸ And, at the same time, how to reconcile "hard-won evidence that could save
15 our lives" with the social constructivist view that is popular among the social sciences?¹⁸⁹ The
16 need to produce an integrative biosocial science in the present of post-genomics¹⁹⁰ may thus
17 require weaving a philosophical filigree that departs from present worldview in the social and life
18 sciences. This view, open to complexity thinking, should be capable of accounting for a shared
19 idea of a socially situated biology.¹⁹¹ What is, then, the role that Waddington's attempt to achieve
20 this goal through an organicist philosophical project may play for such an endeavor?¹⁹²

21 As Maurizio Meloni has argued,¹⁹³ it is important to recognize that the relationship between
22 science and politics is one of fundamental underdetermination. Epistemic statements are
23 compatible with multiple political values, and the history of biology is indeed full of adversarial
24 uses of the same evidence in the political space – as illustrated by his thorough analysis of
25 Lamarckism and Mendelism at the turn of 20th century. To this point, our work contributes also a
26 methodological pointer underlining the analytical potential of digging into (some of) the historical
27 contingencies¹⁹⁴ that linked our bodies to their environments. Our historical and epistemological
28 parallels provide a multi-layered interpretation of today's attempts to interpret the bio-social
29 nexus that links our biology with its material, social and cultural environments. Epistemic
30 practices around plasticity in contemporary epigenetics offer us the return of traditions, which –
31 as we have partly reconstructed here – do not align with the Waddingtonian genealogical tree
32 (re)constructed by the epigenetic orthodoxy¹⁹⁵. These very same traditions, we argue, offer us also
33 the possibility to recognize distinct facets of the biosocial as: (i) ontological conceptions of the

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1 unity of life as social and biological phenomenon, (ii) calls for epistemic hybridity across social
2 and biological sciences, and (iii) injunctions towards biopolitical governing of our plastic bodies.
3 These different facets of the biosocial are yet to become fixed theoretical and political options in
4 the present of post-genomics. As traces of the biosocial, they could therefore serve as
5 methodological and heuristic guide for approaching critically the assumptions, values, (social)
6 ontologies and political leanings currently populating the field of epigenetics.

¹ We will not delve here into an analysis of cognate uses of 'plasticity' in contemporary neuro- and cognitive sciences. Although notions of biological and neural plasticity are certainly interwoven, here we focus on the debate that predates a consideration of functions and psychology of the brain as an epistemic space for biological and medical sciences (see: C. A. Logan, 'Engrams and Biological Regulation: What Was "Wrong" with Organic Memory?', *Memory Studies* 8, no. 4 (1 October 2015): 407–21). For an analysis of the multiple ways in which contemporary uses of plasticity in biology crosscut those in neurosciences, see: D. Papadopoulos, 'The Imaginary of Plasticity: Neural Embodiment, Epigenetics and Ecomorphs', *The Sociological Review* 59, no. 3 (August 1, 2011): 432–56.

² A.P. Feinberg, 'Phenotypic Plasticity and the Epigenetics of Human Disease', *Nature* 447, no. 7143 (May 24, 2007): 433–40.

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⁸ S. Müller-Wille and H.-J. Rheinberger, eds., *Heredity Produced: At the Crossroads of Biology, Politics, and Culture, 1500-1870, Transformations* (Cambridge, Mass: MIT Press, 2007).

⁹ M. Pigliucci, *Phenotypic Plasticity: Beyond Nature and Nurture* (Baltimore: Johns Hopkins University Press, 2001); A. Nicoglou, 'The Evolution of Phenotypic Plasticity: Genealogy of a Debate in Genetics', *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences* 50 (1 April 2015): 67–76.

¹⁰ M. Meloni, *Political Biology*, (Basingstoke, Hampshire ; New York, NY: Palgrave Macmillan, 2016); Meloni, *Impressionable Biologies*, ch.1; Tatjana Buklijas, 'Histories and Meanings of Epigenetics', in *The Palgrave Handbook of Biology and Society*, eds. Maurizio Meloni et al., pp.167-87.

¹¹ See Meloni, *Impressionable Biologies* for a similar approach mobilizing pre-modern views of the plastic body.

¹² G. Nicolosi and G. Ruivenkamp, 'The Epigenetic Turn', *Medicine, Health Care and Philosophy* 15, no. 3 (1 August 2012): 309–19, <https://doi.org/10.1007/s11019-011-9342-z>.

¹³ I. Hacking, 'Language, Truth and Reason', in *Rationality and Relativism*, ed. Martin Hollis and Steven Lukes (MIT Press, 1982), 48–66.

¹⁴ L. Daston, 'Historical Epistemology', in *Questions of Evidence: Proof, Practice, and Persuasion Across the Disciplines*, ed. James K. Chandler, Arnold Ira Davidson, and Harry D. Harootian (University of Chicago Press, 1994), 282–289.

¹⁵ R. Geuss, 'Genealogy as Critique', *European Journal of Philosophy* 10, no. 2 (1 August 2002): 209–15.

¹⁶ N. Carey, *The Epigenetics Revolution: How Modern Biology is Rewriting Our Understanding of Genetics, Disease and Inheritance* (London: Icon Books, 2012).

¹⁷ S. Shapin, 'History of Science and Its Sociological Reconstructions', *History of Science*, 21 July 2016.

¹⁸ J. A. Caron, "'Biology" in the Life Sciences: A Historiographical Contribution', *History of Science* 26, no. 3 (September 1988): 223–68.

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¹⁹ C. H. Waddington, 'The Epigenotype', *International Journal of Epidemiology* 41, no. 1 (1 February 2012): 10–13, <https://doi.org/10.1093/ije/dyr184>. See also Meloni, *Impressionable Biologies* for a longer, pre-modern history of the plastic body in epigenetics.

²⁰ Ingold and Pálsson, *Biosocial Becomings*; Meloni et al., *Biosocial Matters*; Meloni et al., *The Palgrave Handbook of Biology and Society*.

²¹ Ecological themes and environmental theories of health have dominated medical practices and views around the globe for several centuries. The history of plasticity thinking is certainly interwoven with that of views of the body and its alterations resulting from environmental changes. Several historians and sociologists have provided an analysis of these developments both in Western contexts and beyond. Addressing in full how notions of plasticity in the period we selected intertwine with different understandings of the body and the environment goes however beyond the scope of the present analysis. For an analysis of the longer history of plasticity in pre-modern times, see: Meloni, *Impressionable Biologies*. For an analysis of environmental theories of health beyond Western contexts, such as Arabic, Hindu and other ethno-medical regimes around the world. See: E. V. Daniel, *Fluid Signs: Being a Person the Tamil Way* (University of California Press, 1987); F. Zimmermann, 'The Jungle and the Aroma of Meats: An Ecological Theme in Hindu Medicine,' *Social Science & Medicine* 27, no. 3 (1 January 1988): 197–206; W. Anderson, *Colonial Pathologies: American Tropical Medicine, Race, and Hygiene in the Philippines* (Duke University Press, 2006).

²² C. J. Glacken, *Traces on the Rhodian Shore: Nature and Culture in Western Thought from Ancient Times to the End of the Eighteenth Century* (University of California Press, 1967).

²³ Plato, *Theaetetus*, trans. Joe Sachs, (Newburyport, MA: Focus, 2004).

²⁴ C. Malabou, *The Future of Hegel: Plasticity, Temporality, and Dialectic* (New York: Routledge, 2005).

²⁵ Glacken, *Traces on the Rhodian Shore*.

²⁶ T. Rees, *Plastic Reason: An Anthropology of Brain Science in Embryogenetic Terms* (Oakland, California: University of California Press, 2016).

²⁷ Following Hans Blumenberg's metaphorology – H. Blumenberg, *Paradigms for a Metaphorology* (Cornell University Press, 2010) – 'plasticity' could be considered as (what the author calls) an "absolute metaphor"; namely, a heuristic "invested with a pragmatic function" that makes intelligible a great spectrum of phenomena whose empirical and conceptual foundations prove "resistant to terminological claims" (pp.4-5). In this view, plasticity thinking should not be regarded as a theoretical and/or empirical determination of bodies-environments entanglements that is confined to life sciences' reflections. Rather, plasticity as absolute metaphor is an intuitive/symbolic resource orienting reflections, practices and uses of bodies' porosity across different domains. Historically in fact, as argued by philosopher Catherine Malabou (C. Malabou, *Ontology of the Accident: An Essay on Destructive Plasticity*, Cambridge: Polity Press, 2012), the notion of plasticity has enabled different reflections around an ontology of becoming set in contrast to modern, static views of nature and the self. This ontology, Malabou shows, can be found in science, art, philosophy as well as educational sciences. Our paper sets out to analyze uses of plasticity that have enabled – and still enable – biological thinking about the openness of our bodies to their social and material environments. This notwithstanding, it is worth underlining that the scientific practices we describe here intersected with cultural practices grappling with plasticity beyond the life sciences. Specific examples of this crosstalk across science and socio-cultural practices could be found in the analysis of the historical cases we present.

²⁸ Caron, "'Biology" in the Life Sciences,' C. López-Beltrán, 'The Medical Origins of Heredity,' in S. Müller-Wille and H.-J. Rheinberger, *Heredity Produced: At the Crossroads of Biology, Politics, and Culture, 1500-1870*, (Cambridge, Mass: MIT Press, 2007), pp.105–32.

²⁹ S. Müller-Wille and C. Brandt, *Heredity Explored: Between Public Domain and Experimental Science, 1850-1930* (MIT Press, 2016).

³⁰ Meloni, *Impressionable Biologies*.

³¹ M. Foucault, *Society Must Be Defended: Lectures at the Collège de France, 1975-76*, ed. Mauro Bertani et al., (New York: Picador, 2003), p.241.

³² I. Hacking, 'The Looping Effects of Human Kinds,' in *Causal Cognition: A Multidisciplinary Debate*, eds. D. Sperber, D. Premack, D., and A. James Premack (Oxford: Oxford University Press, 1996), pp.351–94. See also Foucault, *Society Must Be Defended*.

³³ Müller-Wille and Rheinberger, *Heredity Produced*; Müller-Wille and Brandt, *Heredity Explored*.

³⁴ Meloni, *Impressionable Biologies*.

³⁵ A comprehensive history of plasticity in the timeframe we selected would require to discuss other major milestones of its theorizations: from Charles Darwin's (1809-1882) theory of pangenesis, to Wilhelm Ludwig Johannsen's (1857-1927) distinction between genotype and phenotype, Richard Woltereck's (1877-1944) reaction norm, and Ivan Ivanovich Schmalhausen's (1884-1963) theorization of developmental plasticity within the framework of neo-Darwinism (see Pigliucci, *Phenotypic Plasticity* and Nicoglu, 'The Evolution of Phenotypic Plasticity'). Yet, the historical instances we investigate enable us to draw a straightforward parallel with the epistemologies of plasticity in contemporary epigenetics. Yet, we do not mean to exclude that different past-to-present analogies may reveal other insights into contemporary epigenetics. For instance, a historico-epistemological analysis of how intergenerational

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transmission became a concern for biological knowledge-making about conception across the 19th and 20th centuries may reveal themes in current studies on epigenetic gestational programming that we do not explore here (see C. Arni, 'The Prenatal: Contingencies of Procreation and Transmission in the Nineteenth Century', in Müller-Wille and Brandt, *Heredity Explored*).

³⁶ J. Golinski, *British Weather and the Climate of Enlightenment* (University of Chicago Press, 2010). D. Porter, *Health, Civilization and the State: A History of Public Health from Ancient to Modern Times* (Routledge, 2005), <https://doi.org/10.4324/9780203980576>.

³⁷ L. Loison, 'French Roots of French Neo-Lamarckisms, 1879–1985,' *Journal of the History of Biology* 44, no. 4 (1 November 2011): 713–44.

³⁸ J.B. Lamarck, *Philosophie Zoologique*, Dentu (Paris, 1809), p.144.

³⁹ Before the French Revolution of 1848, public and private hygiene develops in France without any great relation to natural history. We note, however, that the project of a positive neo-Lamarckian biology – grounded on mechanical explanations of the deterministic relationship between organism and milieu – was formulated in the middle of 19th century in France as a complementary endeavor to hygienism; see L. Loison, *Les Notions de Plasticité et d'hérédité Chez Les Néolamarckiens Français (1879-1946): Éléments Pour Une Histoire Du Transformisme En France* (Nantes, 2008) .

⁴⁰ Cf. G. Jorland, *Une société à soigner: Hygiène et salubrité publiques en France au XIX^e siècle* (Paris: Gallimard, 2010).

⁴¹ In French, the word 'metabolism' was used for the first time in 1858 in the field of chemistry and was meant to cover the ensemble of internal molecular changes of the body instrumental to maintain life; see Oxford English Dictionary online, 'Metabolism, N.,' (Oxford University Press, 2001), <http://www.oed.com/view/Entry/117160>.

⁴² E. Tourtelle and J.-N. Hallé, *Hygiène*, Encyclopedie des sciences medicales (Paris, 1837), p.137; our translations henceforth; our emphasis.

⁴³ A conception that very much resounds with the one purported in the 1850s by Claude Bernard (1813-1878): "Medicine possesses life modifiers. [...] All the science consists therefore of knowing how to handle these modifiers in a safe way, through the knowledge of the laws governing the body healthy, sick and modified by drug actions" (C. Bernard, *Principes de Médecine Expérimentale (1858-1877)*, Université du Québec, Les Classiques Des Sciences Sociales (Chicoutimi, 2003), p.35). Yet, it is worth noting how experimental medicine in Bernard's view pertained to the action of these modifiers in the "internal milieu" (p.38) of the body.

⁴⁴ Tourtelle and Hallé, *Hygiène*, p.xii.

⁴⁵ C. E. Perrin, 'Revolution or Reform: The Chemical Revolution and Eighteenth Century Concepts of Scientific Change,' *History of Science*, 21 July 2016.

⁴⁶ For instance, equivalent approaches emphasizing bodily processes of self-healing can be found also in German-speaking contexts. See: J. Bleker, 'Biedermeiermedizin — Medizin Der Biedermeier? Tendenzen, Probleme, Widersprüche 1830—1850', *Medizinhistorisches Journal* 23, no. 1/2 (1988): 5–22; E. Lesky, 'Von Den Ursprüngen Des Therapeutischen Nihilismus', *Sudhoffs Archiv Für Geschichte Der Medizin Und Der Naturwissenschaften* 44, no. 1 (1960): 1–20.

⁴⁷ Louis Vitet, Leroy, and Société de Médecine de Lyon, *Médecine expectante* (Chez Amable Leroy, 1803).

⁴⁸ Jorland, *Une société à soigner*, p.13.

⁴⁹ Models of policing population health have developed in the 18th century on the basis of different epistemic and political conditions. For an overview on the rise of public health across different European contexts, see: G. Rosen, *A History of Public Health*, revised expanded edition (Baltimore: Johns Hopkins University Press, 2015); D. Porter, *Health, Civilization and the State: A History of Public Health from Ancient to Modern Times* (London: Routledge, 2005).

⁵⁰ Tourtelle and Hallé, *Hygiène*, p.iv.

⁵¹ Müller-Wille and Brandt, *Heredity Explored*.

⁵² Müller-Wille and Brandt, *Heredity Explored*, p.13.

⁵³ Y. Delage, *La Structure Du Protoplasme et Les Théories Sur l'hérédité et Les Grands Problèmes de La Biologie Générale* (Paris: Reinwald & C., 1895).

⁵⁴ Delage, *La Structure Du Protoplasme*, p.185.

⁵⁵ Delage, *La Structure Du Protoplasme*, p.423.

⁵⁶ Delage, *La Structure Du Protoplasme*, p.213-214.

⁵⁷ Müller-Wille and Brandt, *Heredity Explored*, p.8.

⁵⁸ E. Haeckel, *Essais de Psychologie Cellulaire* (Paris: Germer Billière et C., 1880), p.89.

⁵⁹ E. P. Jacobsen, *From Cosmology to Ecology: The Monist World-View in Germany from 1770 to 1930* (Peter Lang, 2005), p.106.

⁶⁰ Haeckel, *Essais de Psychologie Cellulaire*, p.87.

⁶¹ Haeckel, *Essais de Psychologie Cellulaire*, p.77.

⁶² Haeckel, *Essais de Psychologie Cellulaire*, p.80 ; emphasis added.

⁶³ A. Reynolds, 'Ernst Haeckel and the Theory of the Cell State: Remarks on the History of a Bio-Political Metaphor,' *History of Science* 46, no. 2 (June 2008): 123–52.

⁶⁴ Haeckel, *Essais de Psychologie Cellulaire*, p.131.

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⁶⁵ Haeckel, *Essais de Psychologie Cellulaire*, p.131; original emphasis.

⁶⁶ Haeckel, *Essais de Psychologie Cellulaire*, p.18.

⁶⁷ Haeckel, *Essais de Psychologie Cellulaire*, p.130.

⁶⁸ Haeckel, *Essais de Psychologie Cellulaire*, p.19. See also Reynolds 'Ernst Haeckel and the Theory of the Cell State.'

⁶⁹ We will not delve here into the limitations and allegations of fraud in Haeckel's work; see: N. Hopwood, *Haeckel's Embryos: Images, Evolution, and Fraud* (Chicago: University of Chicago Press, 2015).

⁷⁰ U. Hossfeld and L. Olsson, 'The Road from Haeckel: The Jena Tradition in Evolutionary Morphology and the Origins of "Evo-Devo",' *Biology and Philosophy* 18, no. 2 (2003): 285–307.

⁷¹ Hopwood, *Haeckel's Embryos*. As argued by Dombrowski, Haeckel's illustrations show "the powerful role of rhetoric and ethics in scientific discourse in two ways." On the one hand, his drawings epitomize how science could be made relevant across "different branches of human thought and action." These images, the author shows, have influenced popular representations of development and evolution throughout the 20th century. On the other hand, the accusations of fraud moved to these representations also show "the importance of ethos in technical and scientific discourse, and the damage that can follow from ethical lapses in visual communication". Haeckel's misrepresentations of embryological development have undermined not just his credibility, but also neo-Darwinian evolutionary thinking among creationists. See P. Dombrowski, 'Ernst Haeckel's Controversial Visual Rhetoric', *Technical Communication Quarterly* 12, no. 3 (1 July 2003): 303–19, pp. 303-304.

⁷² The social ontology implicit in Haeckel's theory of organic memory has both constituted the basis for reactionary politics in fascist ideologies and inspired more progressive views of social development and eugenic policies at the beginning of the 20th century. See: D. Gasman, *Haeckel's Monism and the Birth of Fascist Ideology*, 2nd ed. edition (New York: Peter Lang Inc., International Academic Publishers, 1999); Logan, 'Engrams and Biological Regulation.' See also Meloni, *Political Biology* for an extensive analysis of progressive and reactionary interpretations of both Lamarckism and Mendelism.

⁷³ A. Weismann, *Essays upon Heredity and Kindred Biological Problems*, trans. Edward Bagnall Poulton and Arthur Everett Shipley, vol. 1 (Clarendon press, 1889).

⁷⁴ Weismann, *Essays upon Heredity*, p.165.

⁷⁵ Weismann, *Essays upon Heredity*, p.191.

⁷⁶ Weismann, *Essays upon Heredity*, p.165.

⁷⁷ Weismann, *Essays upon Heredity*, p.104.

⁷⁸ A. Weismann, *The Germ-Plasm: A Theory of Heredity* (W. Scott, limited, 1893).

⁷⁹ E. Jablonka and M. J. Lamb, *Epigenetic Inheritance and Evolution: The Lamarckian Dimension* (Oxford ; New York: Oxford University Press, 1995).

⁸⁰ Weismann, *Essays upon Heredity*, pp.310 ff. See also R. G. Winther, 'August Weismann on Germ-Plasm Variation,' *Journal of the History of Biology* 34, no. 3 (2001): 517–55.

⁸¹ Weismann, *Essays upon Heredity*, p.201.

⁸² Weismann, *The Germ-Plasm*.

⁸³ Jablonka and Lamb, *Epigenetic Inheritance and Evolution*, p.37-43. See also Pigliucci, *Phenotypic Plasticity*; Nicoglou, 'The Evolution of Phenotypic Plasticity'; R. G. Winther, 'August Weismann on Germ-Plasm Variation,' *Journal of the History of Biology* 34, no. 3 (2001): 517–55.

⁸⁴ Winther, 'August Weismann on Germ-Plasm Variation,' p.550.

⁸⁵ Weismann, *Essays upon Heredity*, p.201.

⁸⁶ G. B. Jacobi, 'Weismann and Lamarckism,' *The Lancet*, Originally published as Volume 1, Issue 4670, 181, no. 4670 (1 March 1913): 640–41, p.640.

⁸⁷ M. Meloni, 'The Transcendence of the Social: Durkheim, Weismann, and the Purification of Sociology,' *Frontiers in Sociology* 1 (22 July 2016), <https://doi.org/10.3389/fsoc.2016.00011>.

⁸⁸ T. D. Johnston, 'The Influence of Weismann's Germ-plasm Theory on the Distinction between Learned and Innate Behavior,' *Journal of the History of the Behavioral Sciences* 31, no. 2 (1 April 1995): 115–28, [https://doi.org/10.1002/1520-6696\(199504\)31:2<115::AID-JHBS2300310202>3.0.CO;2-K](https://doi.org/10.1002/1520-6696(199504)31:2<115::AID-JHBS2300310202>3.0.CO;2-K).

⁸⁹ A. Dröschner, 'Images of Cell Trees, Cell Lines, and Cell Fates: The Legacy of Ernst Haeckel and August Weismann in Stem Cell Research,' *History and Philosophy of the Life Sciences* 36, no. 2 (1 October 2014): 157–86.

⁹⁰ A. Dröschner, 'Images of Cell Trees, Cell Lines, and Cell Fates.'

⁹¹ Meloni, 'The Transcendence of the Social,' p.6.

⁹² E. L. Peterson, *The Life Organic: The Theoretical Biology Club and the Roots of Epigenetics*, (Pittsburgh, Pa: University of Pittsburgh Press, 2017).

⁹³ Besides the Theoretical Biology Club that gathered scholars from Britain, continental Europe and the United States, this wave of thinkers includes also the affirmation of Lysenkoism as a mainstream position in Soviet Union science. See: E.L. Peterson, 'The Excluded Philosophy of Evo-Devo? Revisiting C.H. Waddington's Failed Attempt to Embed Alfred North Whitehead's "Organicism" in Evolutionary Biology,' *History and Philosophy of the Life Sciences* 33, no. 3

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(2011): 301–20; Peterson, *The Life Organic*; L. Graham, *Lysenko's Ghost: Epigenetics and Russia* (Cambridge, Massachusetts: Harvard University Press, 2016); Meloni, *Political Biology*.

⁹⁴ C. H. Waddington, 'Genetic Assimilation of an Acquired Character,' *Evolution* 7, no. 2 (June 1953): 118; C. H. Waddington, *The Strategy of the Genes* (London New York: Routledge, 1957); C. H. Waddington, 'The Epigenotype,' *International Journal of Epidemiology* 41, no. 1 (1 February 2012): 10–13.

⁹⁵ Waddington, *The Strategy of the Genes*, p.29.

⁹⁶ P. Griffiths, 'The Distinction Between Innate and Acquired Characteristics,' in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2017 (Metaphysics Research Lab, Stanford University, 2017), <https://plato.stanford.edu/archives/spr2017/entries/innate-acquired/>.

⁹⁷ Waddington, *The Strategy of the Genes*, p. 30-31.

⁹⁸ Waddington, 'Genetic Assimilation of an Acquired Character,' p.118.

⁹⁹ Waddington, *The Strategy of the Genes*, p. 167. See also Jablonka and Lamb, *Epigenetic Inheritance and Evolution*; L. Loison, 'Canalization and Genetic Assimilation: Reassessing the Radicality of the Waddingtonian Concept of Inheritance of Acquired Characters', *Seminars in Cell & Developmental Biology* 88 (April 2019): 4–13.

¹⁰⁰ Peterson, 'The Excluded Philosophy of Evo-Devo?'; Peterson, *The Life Organic*.

¹⁰¹ Jablonka and Lamb, *Epigenetic Inheritance and Evolution*, p.32-34.

¹⁰² An extensive analysis of Waddington's legacy would require to distinguish between the early years and the Edinburgh years in his career, as well as between the influence of his ideas in genetics and related fields such as embryology. While, as we explain, his work was not highly regarded among geneticists for the concomitance of theoretical and political factors, his ideas were received differently in the pre- and post-war periods as well as beyond genetics. Through the years until the end of World War II his academic path was highly precarious to the point that the scepticism raised by his theories among neo-Darwinians also threatened the pursuit of his scientific career. The opportunity to join as director the Department of Genetics at the University of Edinburgh in 1947 constituted a turning point in Waddington's career. In Edinburgh, his work acquired a more solid institutional and scientific anchoring. His Epigenetics Laboratory was, as argued by Brian K. Hall, the "largest and perhaps the strongest Genetics department in the United Kingdom" in the 1950s (B. K. Hall, 'Waddington's Legacy in Development and Evolution', *American Zoologist* 32, no. 1 (February 1992): 113–22, p.115). This notwithstanding, Hall and others (e.g. Loison, 'Canalization and Genetic Assimilation') also remind us that the mood of the biological world of the time was not ready for the developmental and integrative ideas developed in Waddington's lab. Coupled with the unfolding of the Lysenko affair, the reductionist and molecular thinking of the Synthesis foreclosed a full uptake of Waddington's ideas in genetics circles (see: Peterson, *The Life Organic*, ch. 8-11). Things stand differently if we look at the impact of Waddington's work in related biological fields, such as embryology. Due to the conceptual and epistemological differences that emerged in the 1930s between genetics and embryology, Waddington's work found greater recognition among the organicist perspectives that largely dominated the latter in 20th century. See S. F. Gilbert (ed.), *A Conceptual History of Modern Embryology* (New York: Plenum Press, 1991), chapter 9; S. F. Gilbert and M. Faber, 'Looking At Embryos: The Visual And Conceptual Aesthetics Of Emerging Form', in *The Elusive Synthesis: Aesthetics And Science*, ed. A.J. Tauber, (Dordrecht: Kluwer Academic Publishers, 1996), 125–51.; R. M. Burian and D. Thieffry, 'Introduction to the Special Issue "From Embryology to Developmental Biology"', *History and Philosophy of the Life Sciences* 22, no. 3 (2000): 313–23.

¹⁰³ Pigliucci, *Phenotypic Plasticity*, p.53. As shown by Peterson, plasticity thinking was indeed isolated during the years following the Modern Synthesis, but nevertheless never disappeared (see Peterson, *The Life Organic*, ch.12). See Pigliucci, *Phenotypic Plasticity*, ch.3 for an analysis of the continuity of plasticity thinking after the period we analyze.

¹⁰⁴ Peterson, 'The Excluded Philosophy of Evo-Devo?'

¹⁰⁵ C. H. Waddington, *The Scientific Attitude*, 1 edition (Routledge, 1948).

¹⁰⁶ Graham, *Lysenko's Ghost*.

¹⁰⁷ Waddington, *The Strategy of the Genes*, p.189.

¹⁰⁸ Peterson, *The Life Organic*.

¹⁰⁹ Waddington, *The Scientific Attitude*.

¹¹⁰ S. M. Squier, *Epigenetic Landscapes: Drawings as Metaphor* (Durham: Duke University Press Books, 2017).

¹¹¹ Waddington, *The Scientific Attitude*, p.172.

¹¹² Although Waddington's production provides several instances of such programmatic ambition to develop a organicist unified theory of social, cultural and biological phenomena, Susan Merrill Squier nicely shows how this objective was not accomplished for several reasons and how this failure still narrows the program of contemporary epigenetics. Waddington, she argues, was unable to resist the "canalization" of epigenetics by disciplinary forces that turned his holistic, extensive and visual grasp of biology into a statistically-based, analytical and quantitative understanding that still characterizes the genomic and postgenomic eras. See: Squier, *Epigenetic Landscapes*, chapters 1, 2 and Conclusions.

¹¹³ Waddington, *The Scientific Attitude*, p.172. See also: J. M. W. Slack, 'Conrad Hal Waddington: The Last Renaissance Biologist?', *Nature Reviews Genetics* 3, no. 11 (November 2002): 889–895.

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¹¹⁴ Buklijas, 'Histories and Meanings of Epigenetics'.

¹¹⁵ D. Haig, 'The (Dual) Origin of Epigenetics,' *Cold Spring Harbor Symposia on Quantitative Biology* 69 (1 January 2004): 67–70; R. Holliday, 'Epigenetics: A Historical Overview,' *Epigenetics* 1, no. 2 (2006): 76–80

¹¹⁶ M. Morange, 'The Relations between Genetics and Epigenetics,' *Annals of the New York Academy of Sciences* 981, no. 1 (1 December 2002): 50–60.

¹¹⁷ Roadmap Epigenomics Consortium et al., 'Integrative Analysis of 111 Reference Human Epigenomes,' *Nature* 518, no. 7539 (19 February 2015): 317–30.

¹¹⁸ Y. Atlasi and H. G. Stunnenberg, 'The Interplay of Epigenetic Marks during Stem Cell Differentiation and Development,' *Nature Reviews Genetics* 18, no. 11 (14 August 2017): 643–58, p.645.

¹¹⁹ Indeed, it is not rare for epigenomic scientists to frame themselves as being in full continuity with Waddington's work, see: R. Jaenisch and A. Bird, 'Epigenetic Regulation of Gene Expression: How the Genome Integrates Intrinsic and Environmental Signals,' *Nature Genetics* 33 (1 March 2003): 245–54. Interestingly, newly emerging epigenome-editing possibilities have been welcomed as a technoscientific opportunity to innovate on his legacy. This opportunity has been represented as rendering the conformation of Waddington's landscape a dynamic, ever-changing surface. A movie rendition of this new version of Waddington's model can be found in the online supplementary materials of S. H. Stricker, A. Köferle, and S. Beck, 'From Profiles to Function in Epigenomics,' *Nature Reviews Genetics* 18, no. 1 (21 November 2016): 51–66.

¹²⁰ F. Crick, 'Central Dogma of Molecular Biology,' *Nature* 227, no. 5258 (8 August 1970): 561–63.

¹²¹ L. Moss, 'One, Two (Too?), Many Genes? A Review of "The Concept Of The Gene In Development And Evolution: Historical And Epistemological Perspectives,"' in *Cambridge Studies in Philosophy and Biology*, edited by P. J. Beurton, R. Falk, and H.-J. Rheinberger. Cambridge and New York: Cambridge University Press (March 2003): pp.57–67.

¹²² E. F. Keller, *The Mirage of a Space between Nature and Nurture* (Durham, NC: Duke University Press, 2010).

¹²³ J. R. Dixon et al., 'Chromatin Architecture Reorganization during Stem Cell Differentiation,' *Nature* 518, no. 7539 (18 February 2015): 331–36.

¹²⁴ E. Gjoneska et al., 'Conserved Epigenomic Signals in Mice and Humans Reveal Immune Basis of Alzheimer's Disease,' *Nature* 518, no. 7539 (18 February 2015): 365–69.

¹²⁵ T. M. Powledge, 'Behavioral Epigenetics: How Nurture Shapes Nature,' *BioScience* 61, no. 8 (1 August 2011): 588–92, p.588.

¹²⁶ M. K. Skinner, 'Endocrine Disruptors and Epigenetic Transgenerational Disease Etiology,' *Pediatric Research* 61, no. 5 Part 2 (May 2007): 48R–50R.

¹²⁷ K. Gapp et al., 'Early Life Epigenetic Programming and Transmission of Stress-Induced Traits in Mammals,' *BioEssays* 36, no. 5 (1 May 2014): 491–502.

¹²⁸ M. Szyf, 'Nongenetic Inheritance and Transgenerational Epigenetics,' *Trends in Molecular Medicine* 21, no. 2 (2 January 2015): 134–44.

¹²⁹ Szyf, 'Nongenetic Inheritance and Transgenerational Epigenetics,' p.138. Emphasis added.

¹³⁰ Epigenetic variations as neo-Lamarckian mechanisms of evolution in the received neo-Darwinian theory of evolution are a long-standing matter of controversy in theoretical biology and evolutionary thinking, which far exceeds the contributions we discuss here (see Jablonka and Lamb, *Epigenetic Inheritance and Evolution*). We have privileged however to illustrate this issue as approached by Szyf and Skinner as their research programs enable a description of how actors in contemporary epigenetics operationalize and conceptualize plasticity – as a notion straddling ontogeny and phylogeny – within their experimental practices. See also: Moshe Szyf, 'Lamarck Revisited: Epigenetic Inheritance of Ancestral Odor Fear Conditioning,' *Nature Neuroscience* 17, no. 1 (January 2014): 2–4.

¹³¹ Szyf, 'Lamarck Revisited.'

¹³² The support of mechanisms of neo-Lamarckian inheritance from studies of transgenerational epigenetic inheritance in mammals has been challenged by several authors. See for an overview: Whitelaw, 'Disputing Lamarckian Epigenetic Inheritance in Mammals.'

¹³³ Szyf, 'Lamarck Revisited,' p.3.

¹³⁴ Szyf, 'Lamarck Revisited,' p.4.

¹³⁵ Skinner, 'Environmental Epigenetics and a Unified Theory of the Molecular Aspects of Evolution,' p. 1299.

¹³⁶ A systematic Web of Knowledge search through all the publications of authors "Skinner, Michael K." and "Szyf, Moshe" yielded no results when queried for terms such as: "organic memory", "Ernst Haeckel", "Haeckel", "plastidule".

¹³⁷ See specifically Szyf, 'Nongenetic Inheritance and Transgenerational Epigenetics,' p.136. See also Szyf, 'Lamarck Revisited,' and Skinner, 'Environmental Epigenetics and a Unified Theory of the Molecular Aspects of Evolution.'

¹³⁸ Szyf, 'Nongenetic Inheritance and Transgenerational Epigenetics.'

¹³⁹ M. Szyf, 'Behavior and Epigenetics: Long-Term Plasticity of the Epigenome?,' *Journal of Perinatal Medicine* 38, no. s1 (2010); Z. Hochberg et al., 'Child Health, Developmental Plasticity, and Epigenetic Programming,' *Endocrine Reviews* 32, no. 2 (April 2011): 159–224.

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