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PENULTIMATE DRAFT

Varieties of Parity

Ulrich E. Stegmann, University of Aberdeen, U.K.

Introduction

Developmental Systems Theory (DST) is a fairly loose and varied set of views about development, especially about the role of genes and non-genetic factors. One of the central themes of DST is the idea that organisms inherit much more than simply their DNA (e.g. Oyama 1985, Griffiths and Gray 1994, Sterelny and Griffiths 1999). In addition, DST theorists are sceptical about, and often dismissive of, the idea that genes carry information for development (Griffiths and Gray 1994, Griffiths and Knight 1998, Oyama 2000). Some opponents have also argued that DST rejects as incoherent the notion of 'genes for', as well as the standard methodology of experimentally isolating factors for research purposes (Kitcher 2001). Another issue at the heart of DST revolves around the alleged 'parity' or 'symmetry' between genes and non-genetic factors of development. Parity is the topic of this paper.

A rough characterisation of parity is straightforward: genes are just one kind of developmental factor among many, so there is nothing special about them. On closer inspection, however, the precise content of parity claims is obscure. DST theorists themselves appear to work with different notions and have felt the need for clarification (Griffiths and Knight 1998, Oyama 2000, Griffiths and Gray 2005). The responses by DST sceptics (Schaffner 1998, Godfrey-Smith 2000b, Weber 2005a, Waters 2007) have added further twists. The flourish of parity claims has invited widely diverging views about both their nature and truth. It has been argued, for instance, that parity is essentially the application to biology of a widespread assumption about the metaphysics of causation (Waters 2007). Others recommend recasting parity as a claim about representational content, requiring a project of naturalising semantic content familiar from the philosophy of mind (Shea 2011).

The present state of the debate raises questions about internal consistency. Most DST theorists acknowledge that genetic and non-genetic factors can make very different causal contributions to development whilst insisting that they are on a par. It is unclear how the two claims are meant go together, and whether they can. If one accepts, for instance, that DNA and

enzymes play different causal roles in DNA replication (acting as a template and catalysing reactions, respectively), this implies, on the ordinary understanding of what it is to be a template and to catalyse biochemical reactions, that the base sequence of the daughter strand depends exclusively on the parent strand, not on any enzymes. But if the template determines the product whereas the enzyme assists in its production, in what sense could the former be said to be 'on a par' with the latter? DST theorists may dismiss the distinction between 'determining' and 'assisting'. But how could they do so without thereby negating what they profess to acknowledge, i.e. that templates and enzymes play different causal roles?

My goal in this paper is to clarify the parity claims of DST. To this end I will distinguish and evaluate several distinct notions of parity, not all of which are endorsed by DST theorists. The versions I distinguish here are not intended as a comprehensive list and they certainly do not exhaust the logical space of possible interpretations. Nor is my primary interest in a quasi-historical overview of how various authors in the DST tradition have interpreted parity. Instead I aim to capture the most influential versions in the debate thus far.

1. Interactionism and Causal Indistinctness

The first version of parity is simply the claim that development is caused by a *variety* of factors, not just by genes. Consider the following remark by Oyama (1985, p. 15): "What I am arguing for here is a view of causality that gives formative weight to all necessary influences, since none alone is sufficient for the phenomenon or for any of its properties". This statement appears to emphasise the fact that the causation of development involves multiple causes, all of which are necessary and none of which is sufficient on its own. Genes alone do not produce anything, let alone phenotypes (nor does any other molecule). As Schaffner (1998, p. 234) saw, this is one plausible sense in which genes and non-genes are on a par: "[…] *causally*, genes have parity with other molecules as severally necessary and jointly sufficient conditions (to produce traits) […]".

> Parity 1 (interactionism): Genetic and non-genetic factors are on a par insofar as both are causally necessary for development.

This form of parity is neither new nor controversial. It articulates the consensus position in developmental biology, sometimes called 'interactionism' (see for example Oyama 2000, Robert 2004). Interactionism, or at least a prominent version of interactionism, is "the view that neither genes nor environments, neither nature nor nurture, suffices for the production of

phenotypes" (Robert 2004, p. 2). And this, as DST theorists have noted themselves, is the orthodox view of development: "No one honestly believes that development can be achieved unilaterally by genes acting alone or in concert. Rather, everyone agrees that genes are important to, but not sufficient for, development" (Robert 2004, p. 1). So if the parity thesis of DST is to be more than a truism, it must be something else.

A more interesting version of parity emerging from Schaffner's (1998) discussion was the claim that genes do not make unique contributions to development; that they lack any specific set of causal roles. Weber (2005a, p. 260) called this the "strong version" of parity: it "says that DNA and genes play no causal role that sets them apart from other developmental systems components. In other words, there is no causal role difference whatsoever […]". In effect, this form of parity takes interactionism as its starting point and then adds a claim about the lack of difference in the kind of contributions made.

> Parity 2 (causal indistinctness): Genetic and non-genetic factors are on a par insofar as they do not differ in their (causal) contributions to development.

Griffiths and Knight (1998, p. 254) swiftly rejected this interpretation of parity as a "'strawman' parody of developmentalism". Many DST theorists are adamant that parity allows different causal factors to make distinct contributions to development (e.g., Griffiths and Gray 1994, 2005, Oyama 2000, Stotz 2006).[1]

It is tempting to associate interactionism and causal indistinctness with the parity claims of DST. But neither comes close to what DST theorists appear to have in mind. The versions of parity in the following sections, by contrast, are portrayed by at least some DST theorists as the intended content.

2. Millean Parity

Bearing in mind the insistence of DST theorists on causal differences, Weber (2005a, p. 260) articulated a "weak version" of parity in a previous attempt at clarification: "The *weak* version says only that there is no *categorical* difference, that is even though there are some

[1] Here are two quotes to this effect: "The theory does not deny that there are distinctions among developmental processes" (Griffiths and Gray 1994, p. 283). Oyama (2000, p. S342) wrote: "Nor does parity mean that in any particular analysis, all things are equally important or "the same," that no distinctions can be made."

differences in causal roles between DNA and genes, the latter do not belong to a separate category of developmental causes". A 'categorical difference' between genes and non-genes, Weber (2005a) continued, could only mean that they fall into different *ontological* categories. And since philosophical orthodoxy holds that causes do not fall into different ontological categories, genetic and non-genetic factors are on a par insofar as both belong to one, undivided category: causes.[2] Weber here alluded to John Stuart Mill's view according to which the practice of distinguishing genuine causes from mere conditions (causal selection) is "capricious" and does not trace a metaphysical difference.

Waters (2007) agrees with this reading. In fact he believes that this form of parity constitutes "the basic logic of causal parity arguments" generally (p. 572):

> "[Arguments for causal parity in complex biological systems] typically start with the premise that the kind of element emphasized by scientists as the cause of a given process is actually *just* one of many causes of the process. Parity arguments then claim that picking out one cause, when in fact there are many, cannot be justified on ontological grounds because, after all, causes are causes." (Waters 2007, p. 553)

Parity in Mill's sense starts by embracing interactionism and then adds a *metaphysical* claim about the nature of causation. Unlike causal indistinctness, Millean parity allows for *empirical* differences. DNA templates, for instance, do different things than DNA polymerases (providing hydrogen binding sites vs. catalysing covalent bonds); their sameness lies in belonging to the ontological category of causes.

> Parity 3 (Millean parity): Genetic and non-genetic factors are on a par insofar as both are causes and causes constitute a uniform ontological category (specifically, there is no ontological difference between causes and conditions).

Parity in this sense is simply the application of Mill's doctrine to molecular genetics. Biologists habitually pick out the DNA parent strand as 'the' cause of the daughter strand, especially of its base sequence, although its production also requires the presence of DNA polymerase. Both factors are required for DNA replication (interactionism). Millean parity goes

[2] Weber argued against this form of parity that it ceases to be an empirical proposition. Its truth hinges on a general metaphysical claim about the nature of causation (section 8.4).

further in maintaining claim that, since both are causes, it is unjustified and misleading to claim that templates 'determine' base sequences whereas polymerases only 'assist'.

Some DST proponents do seem to work with parity in this ontological sense.[3] Waters (2007) cites Robert's (2004) and Moss' (2003) work. Consider, for example, Robert's (2004) advocacy of "causal dispersion (distributed control)", which he characterises as follows: "causal power is not contained within any particular entity or class of entities but rather resides in the contingent relations between developmental interactants within such networks" (p. 116). This may read like a restatement of interactionism, but a more charitable reading suggests a separate idea. Robert's reserves the term 'causal co-interactionism' for the "joint determination by multiple causes" (p. 115), and hence for interactionism. Therefore, 'causal dispersion' may be understood as emphasising the equal distribution of causal *power*. And this can be taken to mean that, since all contributions exert *equal* causal power, there is no justification for distinguishing 'genuine' causes from mere conditions.

Waters (2007) has challenged Millean parity on the grounds that, contrary to standard assumptions, there *is* an ontological difference between causes and conditions.[4] He argues that what we regard as 'the' cause of an effect tends to pick out a specific ontological category, what he calls "the actual difference maker". The actual difference maker (ADM) is the cause[5] that makes the difference with respect to a set of actual effects. Not all causes are like that; for instance, some causes make a difference to *potential* effects. Waters then argues that only nucleic acids are the ADMs of their templating products. Enzymes are causes, too, but not the ADMs (2007, pp. 573-4). Consider the entire set of RNA molecules in a single bacterium at a particular point in time. The RNA molecules have different sequences and were produced by the interplay of many causal factors. Of all the causal factors only DNA templates (or "activated genes") differ from one another (in their sequences). Other causes, like the set of different RNA polymerase molecules, have the same structure (bacteria have just one sort of polymerase). Since only DNA templates are the ADMs of the new RNA sequences, the templates are not on a par with enzymes.

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[3] Not all accept Millean parity. Paul Griffiths, for instance, accepts that templates are the only factors determining product sequences *if* mechanisms like RNA editing are absent (pers. comm.).

[4] In addition, Waters (2006) offers a methodological defence of 'gene-centrism', the phenomenon that genes are the focus of much research in the life sciences.

[5] Waters (2007) builds on Woodward's (2003) manipulationist account of causation.

Waters maintains that in ordinary contexts, like those in the bacterial cell above, both DNA and its causal effects (but not non-genetic factors) take on a range of values, and that therefore DNA happens to be the ADM. If true this would be enough to establish an ontological difference in causal status between DNA and non-genetic factors in these contexts.[6] But Waters claim is more ambitious. It is that causal selection traces ADMs and that, specifically, talk of DNA as 'determining' sequences reflects its status as the ADM. This is a stronger claim because it asserts, not only *that* DNA is the ADM of product sequences under ordinary circumstances, but also that being the ADM of sequences is what 'determining sequences' consists in. I disagree with the latter claim.[7]

Note first that there are no ADMs without actual differences. If we just consider one particular DNA molecule and its RNA product, then the DNA template is not the product's ADM, because the effect variable (RNA sequence) has just one value. The same holds for the relation between several identical DNA templates and their identical RNA products. Waters notices, and embraces, the radical consequence: DNA does *not* determine the RNA base sequence in these circumstances; it does not exert more influence than the polymerase on what kinds of bases are being incorporated.[8]

This is difficult to accept given that the polymerase is insensitive to the kinds of bases (more on this in the next section). The implication also jars with the history of molecular biology, which suggests that nucleic acid templates have generally been regarded as determining product sequences even in the absence of actual differences. Nierenberg and Matthai's pioneering work on the genetic code is an example. In the experiment that led to the identification of the first

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[6] I owe this point to [omitted for blind review]. See Northcott (2009) for a general objection against Waters (2007) account.

[7] This objection to Waters (2007) is not a criticism of Woodward's (2003) analysis of causation.

[8] "If biologists were […] limited to considering the causal synthesis of a single polypeptide molecule, they would have no basis for saying that the polypeptide's linear sequence was determined by DNA, and not by RNA polymerase. In fact, if restricted to considering a single instance (or a population of identical outcomes), it might appear that DNA was merely scaffolding for the synthesis of RNA. The causal distinctiveness of DNA is in the population. It is only in the context where polypeptide molecules with different amino acid sequences are being synthesized that it makes sense for biologist to say that DNA is not on a causal par with many of the other molecules that play causally necessary roles in the synthesis of RNA and polypeptides". (Waters 2007, p. 579)

'code word', synthetic polynucleotides composed of uracil residues (poly-U) were incubated in a cell-free protein synthesis system. This resulted in polypeptides composed of repetitions of the same amino acid (phenylalanine). There was no actual difference in the effect, since the product molecules were all poly-phenylalanines. Nevertheless, Nirenberg and Matthaei (1961, p. 1601) concluded that "polyuridylic acid appears to function as a synthetic template or messenger RNA" and they described the process as "template RNA-dependent amino acid incorporation". Since templates were regarded as solely responsible for, or determining, amino acid sequences, their conclusion amounts to singling out DNA as 'the' cause of the amino acid sequence, even though there was no actual difference in the cause and effect variables. Other experimenters drew equivalent conclusions, and with respect to both protein[9] and RNA synthesis[10]. In these cases at least, singling out DNA as the determining cause did not trace ADMs.

What do the examples show? One response is to say that actual scientific practice may well be at odds with what the data justify. But the historical examples reflect the *general* practise among working scientists, not rare exceptions. So it is challenging to explain away their best judgments as unjustified, especially given that the ADM account is meant be in line with actual scientific practice, e.g. with "how geneticists explained their experimental results" (Waters 2007, p. 556).

Another response starts by emphasising that the authors based their conclusion not merely on the poly-U experiment but rather on the wider set of trials reported in the paper.[11] For

[9] For instance, Nishimura *et al.* (1965) produced polypeptides containing serine and leucine in alternating order from poly-UC, describing the latter as "directing" polypeptide synthesis (pp. 314, 323).

[10] Examples are the production of polyadenylate RNA fragments from polythymidilate DNA (Falaschi et al. 1963) and of poly-UC RNA molecules from poly-TG DNA sections (Nishimura et al. 1965). The DNA fragments were regarded as "templates" for synthesising the RNA fragments (e.g. Falaschi et al. 1963, p. 3084, Nishimura et al. 1965, p. 322), whose function is to *determine* RNA sequences (Falaschi et al. 1963, p. 3080).

[11] Many thanks to [omitted for blind review] for pressing me on this point. In fact, both Judson's (1979, p. 477-8) account of this historical episode and the structure of Nirenberg and Matthaei's (1961, p. 1601) paper suggest that they considered the wider set of trials as decisive for their conclusion.

instance, Nierenberg and Matthaei tested polynucleotides other than poly-U[12] and found that they did not generate a polypeptide. And in the context of these trials, the poly-U template *was* the ADM: the difference in the cause variable (poly-U as opposed to some other template) fully accounts for the difference in the effect variable (roughly, polypeptide present or absent). Note, however, that the larger set of trials also included experiments in which *amino acids* were the ADMs for polypeptides: when the same kind of template was used in solutions with different sorts of amino acids available, only the tube containing phenylalanine yielded a polypeptide.[13] These experiments feature the same effect variable as before (polypeptide present or absent), but now the cause variable that actually differs are kinds of amino acids (phenylalanine as opposed to the other amino acids tested). On the ADM account, the conclusion that DNA determines the new sequences would not be justified with respect to the trials in which DNA was not the ADM (e.g. the poly-U and phenylalanine trials). And this implies that Nirenberg and Matthaei somehow discounted or ignored these trials when drawing their conclusion about the determining role of DNA templates. Yet the opposite appears to be the case: these trials were a crucial part of their evidence. My conclusion is that the 'determining' role of templates should not be understood in terms of actual difference making (Stegmann 2012 explores an alternative).

3. Millean capriciousness

Lisa Gannett (1999) is another DST theorist who seems to embrace Millean parity. But in one important respect, Gannett takes it a step further. She advances a pragmatic understanding of genetic traits, maintaining that causal selection in genetics is heavily dependent upon pragmatic interests. Indeed, any kind of cause might be selected as 'the' cause given suitable social or technological circumstances:

> "I argue that practical choices determine how cause-condition distinctions are drawn […]" (Gannett 1999, p. 351). And further: "I argue that genetic explanations are pragmatic, or in other words, that practical, *not theoretical*, considerations direct the singling out of genes as causes" (p. 356). "Given that explanations are contextually determined by the aims,

[12] For instance, polyadenylic acid (poly-A) and polycytidylic acid (poly-C); table 6, 'experiment no. 1' in Nirenberg and Matthaei (1961, p. 1601).

[13] Poly-U served as the template. See table 8, as well as text on p. 1596, in Nirenberg and Matthaei (1961).

> interests, and orientations of those who seek them, it is hardly surprising that *any number of conditions might be selected as "the" cause* of a given event" (p. 358). (My italics).

Gannett mentions several pragmatic concerns, among them the effectiveness of treatments for diseases and the professional interests of molecular geneticists as a scientific community. Gannett's remarks suggest a view that pushes the pragmatic aspect of Millean parity to the extreme. Millean parity, while allowing pragmatic goals to influence causal selection, leaves room for non-pragmatic influences. It is compatible with the idea that causal selection is partly driven by principles which reflect, or aim to reflect, empirical differences and which persist over local and fleeting interests. One might require, for instance, that 'the' causes be identified with causes that make a difference relative to some specified context. Such general methodological principles would serve pragmatic aims and would not trace an ontological difference (if Millean parity is true). But there would be no denying that causal selection follows principles of this kind. However, one might propose to dispense with such principles altogether. On such a view, 'Millean capricousness', causal selection entirely depends on pragmatic concerns; it is guided by any number of interests, as fickle and arbitrary as they may be.

> Parity 4 (Millean capriciousness): Genetic and non-genetic factors are on a par insofar as both are causes, and causes constitute a uniform ontological category, and causal selection is wholly determined by pragmatic, context-sensitive forces.

Applied to DNA replication, Millean capricousness implies that purely local, pragmatic interests are responsible for the habit of selecting the template as 'the' cause of the daughter strand. Molecular biologists have a "professional stake in maintaining the focus on the causal efficacy of genes" (Gannett 1999, p. 359) and so, her reasoning seems to go, they select templates as the cause. It would then be equally plausible to suggest that a new breed of ambitious enzymologists may one day select DNA polymerase as 'the' cause, if only this move strikes them as promoting their goals.

It is implausible, however, that causal selection is "capricious" in this strong sense. Adding an adenine to the growing DNA strand counterfactually depends on there being a thymine in the parent strand. And, true enough, it also depends counterfactually on the presence of DNA polymerase as well as a host of other factors and conditions. This is the symmetry that creates the problem. But note that the *contrast*, adding adenine rather than a different base, does *not*

counterfactually depend on DNA polymerase. As molecular biologists point out, DNA polymerase is insensitive to the chemical nature of the nucleotides it conjoins; it makes no difference as to *which* base is added. The contrast is explained by the parent base, not the DNA polymerase. It seems reasonable to conclude that causal selection in this case is guided by the principle to explain certain contrasts.

Indeed, additional principles seems to be at work. There is at least one factor other than parent bases that accounts for the same contrast, but that is not selected as 'the' cause: the base pairing rules or, more precisely, the facts underlying these rules, such as the requirement for complementarity, the existence of four types of bases, and so on. Suppose the thymine-adenine rule was to change to thymine-thymine (assuming this would be chemically possible), then the thymine in the template would yield another thymine, not an adenine. Hence, the fact that adenine, rather than a different base, is being added in replication (as we know) it depends counterfactually on the base pairing rule being thymine-adenine. Now, the base pairing rules do not change from one base pairing to the next, whereas the kind of parent base does frequently. This suggests that causal selection with respect to replication is also underpinned by considerations about constant factors. That is, molecular biologists seem to relegate constant causal factors like the base pairing rules to the background, while considering varying factors as candidates for 'the' causes.

In sum, privileging templates is not a matter of Millean capriciousness. The practice seems rather based on selecting as 'the' cause whichever causal factor best explains the relevant contrast and is, moreover, a varying factor. This principle allows a systematic way of selecting causes. Even enzymologists will not dispute that, once the focus is on explaining contrasts, there is a matter of fact about contrasts depending counterfactually on the template bases. Perhaps there is room to argue that this principle ultimately depends on pragmatic interests (Millean parity). It would be implausible, however, to suggest that no such principle operated in the first place.

4. The No Dichotomies-View

Some DST protagonists have defended yet another understanding of parity (Griffiths and Gray 1994, 2005, Griffiths and Knight 1998):

> "The real developmentalist position [with regards to parity] is that the empirical differences between the role of DNA and that of cytoplasmic gradients or host-imprinting events do not

justify the metaphysical distinctions currently built upon them" (Griffiths and Knight 1998, p. 254).

Here the starting point is interactionism and the rejection of causal indistinctness. But the "grand, metaphysical distinctions" (Griffiths and Gray 2005) are not equated with ontological distinctions between causes and conditions. Griffiths and co-workers have something else in mind: one of the 'metaphysical' distinctions is the contrast between information carriers and material support; another is the contrast between replicators and interactors (Griffiths and Gray 1994, 2005, Griffiths and Knight 1998, Sterelny and Griffiths 1999); the third distinction is between controllers and the controlled matter (e.g. Sterelny and Griffiths 1999, Oyama 2000). For these authors, parity means that development is not driven by two types of factors differing along several dimensions. Development is not dichotomous.

Parity 5 (no dichotomies-view): Genetic and non-genetic factors are on a par insofar as they do not represent two kinds of factors which play fundamentally distinct roles that differ along several 'metaphysical' dimensions simultaneously. Specifically, the two groups do not divide up such that genes and only genes are information carriers, replicators and controllers, whereas non-genetic factors, and only they, are supporting material, interactors and controlled by genes.

Several variants of this view are conceivable. A weaker variant might accept that the gene/non-gene distinction actually coincides with one or two of the dichotomies, though not with all. Genes and non-genes would then still be on a par with respect to the distinction that does overlap. For example, if both genes and non-genes carried developmental information (in some sense), then they would be on a par informationally, though not with respect to the other two features. This possibility raises the question of the degree of exclusiveness required in order for parity to obtain. Does a single information-carrying non-genetic factor render genes and non-genes informationally on a par? Again, responses of varying strength are conceivable.

The assertion that not only genes are replicated is largely, though not entirely, based on a broadening of the notion of replicator. For example, replicators are regarded as "anything that is reliably replicated in development" (Griffiths and Grey 1994, p. 300) or, slightly less encompassing, "devices with developmental biofunctions" (Sterelny et al. 1996, p. 389). A wide range of phenomena and resources then count as replicators: the songs juvenile birds learn from their parents, nest site imprinting, transmission of endosymbionts, centrioles, basal bodies,

membranes, organelles, DNA methylation patterns, and so on. I share Weber's (2005a) worry that this broadening of 'replication' lumps together a variety of distinct phenomena, especially cultural transmission, the passing on of extrachromosomal material, epigenetic inheritance, and what Weber coined "hereditary replication". The latter is the kind of replication pertaining to Dawkinsian replicators, i.e. the copying of a factor such that a change in that factor will be passed on to future generations and makes a difference to the phenotype it helps to produce. These criteria are not met by most of the factors DST theorists deem to be replicators, e.g. morphogen gradients and cell organelles (Weber 2005a). But a few non-genetic factors do meet these conditions. These are the factors sustaining transgenerational epigenetic inheritance, of which there are now several well-documented examples, including flower symmetries (Cubas et al. 1999), eye colour in *Drososphila* (Seong et al. 2011), and a set of phenotypes in mice (Morgan et al. 1999). On the other hand, transgenerational epigenetic inheritance is likely to be sustained only by DNA methylation, not by histone modifications (Feil and Fraga 2012).

Despite parity claims about the 'control' of development, DST has done little to illuminate this notion, which makes the claims difficult to assess (Weber 2005a). However, progress can be made by considering how the concept is used in molecular and developmental biology. The word 'control' is often applied to causes with particularly significant effects. For instance, many homeobox genes are said to control or direct development because they can switch on entire developmental pathways. The "paradigm of a master control gene", *eyeless*, triggers a cascade of around 2500 other genes, all of which are required for eye development (Gehring 1998, p. 133). Since even master control genes are regulated by further factors, they are better viewed as nodes in a causal network (e.g. Robert 2004, Weber 2005a). This assessment echoes Moss' (1992) observation, made in a different context, that DNA is not the sole *origin* of causal chains. Importantly for our purposes, many environmental factors can also have significant effects on development and in this sense 'control' it. Phenotypic plasticity provides particularly striking examples, such as seasonal morphs in butterflies, temperature-dependent sex determination in turtles, predator-induced morphs in waterfleas (*Daphnia*), and heterophylly in aquatic plants. This kind of control appears to be shared fairly equally among genes and non-genetic factors.

Another kind of control may prove to be much more exclusive. Consider how early automatic looms generated a weaving pattern. A punched-card was fed into the loom and the loom's mechanism then operated depending on the holes in the cards. Every step in this process depended on an external entity (the cards) rather than the previous steps. This is the (intuitive) sense in which the punched cards 'controlled' the machine's operations. As argued by

Stegmann (2012), this sense can be explicated with the help of Woodward's (2003) manipulability account of causation and is the kind of control realised by nucleic acid templates. It remains to be seen how widely this form of control is shared with non-genetic factors.

Woodward's (2010) concept of 'causal specificity' is intended to capture a third kind of control and must be mentioned here briefly. Roughly, causal specificity is the degree to which changes in a cause variable elicit fine-grained changes in the effect variable. Woodward suggests that causal specificity may turn out to confer a causal privilege on DNA. Although a full discussion is beyond the scope of this paper, DNA does not appear to be the only factor exhibiting a high degree of causal specificity (Stegmann 2012, Weber forthcoming).

5. Informational Parity

One aspect of the no dichotomies-view is that genes are not the only carriers of information. According to DST theorists, this should be understood as a conditional: *if* a viable account of information can be provided that applies to genes, then it will apply not to genes alone – the implication being that it is open whether such an account can be provided. Informational parity of this kind figures in several papers (e.g. Griffiths and Gray 1994, Griffiths and Knight 1998, Sterelny and Griffiths 1999) and was articulated succinctly by Griffiths (2001, p. 396): "Any defensible definition of information in developmental biology is equally applicable to genetic and non-genetic factors in development".

> Parity 6 (informational parity): Genes and non-genetic factor are on a par insofar as non-genetic factors will carry information on any viable account of information according to which genes carry information.

While a component of the no dichotomies-view, informational parity is mentioned here separately because it is a distinct idea and because it marks a noteworthy departure from the outright dismissal of genetic information that is also present in the DST literature (Griffiths and Gray 1994, Griffiths and Knight 1998, Oyama 2000).

Informational parity is often defended on the basis of analyses of correlational and teleosemantic accounts of information. For instance, to the extent that genes carry information about phenotypic outcomes because they correlate with them, so do environmental factors, because they also correlate with phenotypic outcomes. Often Dretske's (1981) work is cited in this context as specifying the kind of information at play here. But this can be misleading. Dretske (1981) was concerned with natural information, with what Grice (1957) called "non-

natural meaning", the kind of information surfacing in phrases such as 'the tracks in the snow mean (or carry the information) that a deer walked past'. So, the parity claim would be that both genes and non-genetic factors can carry natural information about phenotypic outcomes. In this respect the link to Dretske's work is well motivated. But it is also worth remembering that Dretske's (1981) *theory* of that type of information hardly supports the parity claim, for his theory applies to neither genes nor non-genetic factors: his theory requires that the occurrence of a gene/non-genetic factor raise the probability of the phenotype to unity, and this condition is unlikely to be satisfied (unless one arbitrarily tailored the channel conditions; but see Weber 2005b). It is more plausible to derive arguments in favour of parity about natural information from considering Shannon's quantity 'mutual information' (Bergstrom and Rosvall 2011) or correlational accounts of information (e.g. Millikan 2004, Scarantino and Piccinini 2010, Shea 2007b). According to the latter, for instance, a factor would carry information about a phenotypic outcome if its occurrence changed (or, on some accounts, increased) the probability of that outcome. And this is true of genes and non-genetic resources alike.

Proponents of teleosemantic accounts of genetic information readily acknowledge that some non-genetic factors carry information about phenotypic outcomes as well (Sterelny et al. 1996, Sterelny 2000, Shea 2007b). Yet the degree of parity is much reduced: only a comparatively small subset of non-genetic factors that carries natural information also carries teleosemantic information. Precisely which subset this is, and hence the total number of non-genetic factors 'on a par' with genes, varies with different teleosemantic accounts. If arbitrariness between cause and phenotype is an ingredient of such an account (as in Maynard Smith 2000 and Sterelny 2000), then microsymbionts are excluded (Sterelny 2000). Dependence on specific reading mechanisms arguably excludes additional factors from being information carriers, e.g. morphogen gradients (Sterelny 2000). A similar result is obtained by requiring that carriers of teleosemantic information be intermediaries between a producing and consuming mechanism, where the producing mechanism has the meta-function of generating heritable phenotypes (Shea 2007a). In addition to restrictions arising from the specifics of the various accounts, all varieties of teleosemantics give rise to an obvious but rarely noticed restriction: since they require information carriers to have evolved in order to produce phenotypic effects, teleosemantic theories exclude nearly all environmental factors of development.[14] Whatever their effect on development, factors like the yearly seasons, ambient temperatures or kairomones did not

[14] Effects of niche construction will complicate the picture.

evolve because of their developmental consequences (or did not evolve at all). They therefore lack teleosemantic information.

Since informational parity was first defended, a few other accounts of genetic information have been proposed (e.g. Godfrey-Smith 2000a, Sarkar 2003, Stegmann 2005). Godfrey-Smith (2000a) has emphasised three specific similarities between the mechanism of protein synthesis and human symbol systems and argued that they motivate talk of coding and information. Interestingly, they are not found in non-genetic mechanisms of development and therefore seem to be unique to protein synthesis. However, it is important to bear in mind that the similarities are taken to represent the reasons why scientists are drawn to informational descriptions; they are not taken to constitute a kind of information. By contrast, Sarkar's (2003) information system is intended as explicating a kind of information. Sarkar identifies certain mapping relations between DNA and its effects which, together with arbitrariness, constitute what Sarkar calls "semiotic information". Sarkar argues that semiotic information happens to be unique to DNA. But there are reasons to doubt this conclusion (see Stegmann 2009, for a detailed discussion).

In sum, at present there seems to be no account of information that applies exclusively to genes. But at least on some teleosemantic accounts, very few non-genetic factors will qualify as information carriers.

6. Distributive parity

A sense of parity related to the no dichotomies-view can be lifted from Godfrey-Smith (2000b), Griffiths and Gray (2005), and Stotz (2006). In the course of clarifying and defending the parity thesis and DST more generally, Griffiths and Gray (2005) invoke the no dichotomies-view. But they also say this: "DNA does play a distinctive set of roles in development, but it does not play just one role (partly because DNA elements are themselves so diverse) and *the important roles those various DNA elements plays [sic] are sometimes played by non-DNA factors* in development" Griffiths and Gray (2005, p. 421, my emphasis). The 'important roles' may well be those featuring in the no dichotomies-view (e.g. carrying information). But the remark can also be interpreted as advocating an overlap between genes and non-genes with respect to a wider range of roles. Stotz's (2006) examples, which are intended to illustrate Griffiths and Gray's (2005) point, suggest as much: sequence specificity (factors other than DNA influence RNA sequences, e.g. splicing and editing agents), inheritance (shared with

methylation patterns, maternal RNA, and so), gene regulation (shared with protein transcription factors, but also environmental factors and regulatory RNAs), and enzymatic activity (which proteins share with certain RNAs, i.e. ribozymes) represent a range of causal roles; no invoking of "grand, metaphysical distinctions" here. Perhaps sequence specificity, inheritance, and gene regulation are intended as causal reformulations of the grand distinctions (information-carrying, replicating and control). But at least one these processes, enzymatic activity, does not exemplify any of them.

In short, parity could be the claim that the causal roles played by genes, however modest, are also played by some non-genetic factor (and *vice versa*). We can further broaden this form of parity by including explanatory contributions other than causal effects, echoing Godfrey-Smith (2000b) reconstruction of parity. Godfrey-Smith construed parity as a claim about any explanatory relations, which included causal relations, but also statistical and semantic relations, as well as "relations involving inheritance".

> Parity 7 (distributive parity): Genetic and non-genetic factors are on a par insofar as every kind of contribution made by a gene is also made by some non-genetic factor, and *vice versa*.

This formulation contains elements none of the above authors may want to endorse. Griffiths and Gray (2005) and Stotz (2006) stop short of arguing that *all* genetic roles are shared by some non-genetic factor, and at least Stotz (2006) seems concerned with causation only. Of course, distributive parity admits of weaker readings: perhaps only most roles are shared, or at least some, and so on. Godfrey-Smith (2000) may have other reservations. For him, the relevant explanatory relations are between genetic/non-genetic factors and *phenotypes*. And this would seem to exclude relations that genes/non-genes have to more proximate features, like reaction products or newly synthesized macromolecules. I prefer including the latter because they are (or can be) aspects of development.

Distributive parity is distinguished from the no dichotomies-view by positing symmetry with respects to *all* sorts of contributions, not merely the "grand" ones. The difference between distributive parity and causal indistinctness may be less obvious because both versions deny causal differences between genes and non-genes. But there really are two ideas here. One is that any specific pair of genetic and non-genetic factors makes the same kind of contribution to development (causal indistinctness). This would imply, for instance, that templates and enzymes play the same causal role in replication, which is plainly false. The second idea (distributive

parity) is that for any genetic factor, there is one or more non-genetic factor playing the same role, and *vice versa.* The corresponding genetic and non-genetic factors need not occur in the same developmental context or even within the same organism. Distribute parity says only that a corresponding factors exists *somewhere*.

Now, the *vice versa*-clause of distributive parity is mistaken. Numerous developmental contributions are the privilege of certain molecules other than nucleic acids. Catalysing the biochemical reactions of phosphorylation and methylation is just one example. There can also be doubts about the extent to which the causal roles of DNA are shared by non-genetic factors. Weber (2005a) has identified 18 roles of DNA and suggested that a few of these may prove to be unique, e.g. the fact that destroying a single DNA token can be lethal to the cell. That these roles are unique is likely, but still open to disconfirmation. But at least Weber's conclusion, that the *combination* of roles is unique to DNA, is well supported. Furthermore, distributive parity may be significantly restricted with respect to the *causal patterns by which* DNA has its (templating) effects. Such patterns are the focus of recent attention and involve causal specificity (Woodward 2010), potential difference making under biologically normal conditions (Weber forthcoming), external ordering (Stegmann 2012), as well as the notion of actual difference making (Waters 2007) discussed in section 2.

In a broader sense, the boundaries between genetic and non-genetic factors have indeed become blurred. Causal roles once thought to be unique to DNA (such as transgenerational inheritance) have been found to be shared with at least one other factor. Conversely, nucleic acids have been found to play roles familiar from non-genetic factors, e.g. certain enzymatic capabilities. DST theorists are right to highlight these findings.

7. Conclusion

The preceding discussion has shown that there is no such thing as 'the parity thesis' of developmental systems theory. Parity claims come in various shapes and sizes. Common qualifications, like causal, weak or strong parity, are valuable. But by themselves they are insufficient to capture the swarm of ideas DST has managed to assemble under one label. The distinctions drawn in this paper, too, may still fall short in this respect. But it seems clear that broad-sweeping assertions to the effect that genes are 'on a par' with non-genetic factors are much too coarse to be evaluable in any meaningful way. We need more fine-grained concepts in order to shed light on the respective roles of genes and non-genetic factors in development.

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References

Bergstrom CT, Rosvall M (2011) The transmission sense of information. Biology and Philosophy 26:159-176

Cubas P, Vincent C, Coen E (1999) An epigenetic mutation responsible for natural variation in floral symmetry. Nature 401:157-161

Dretske F (1981) Knowledge and the Flow of Information. MIT Press, Cambridge, MA

Falaschi A, Adler J, Khorana HG (1963) Chemically synthesized deoxypolynucleotides as templates for ribonucleic acid polymerase. The Journal of Biological Chemistry 238:3080-3085

Feil R, Fraga MF (2012) Epigenetics and the environment: emerging patterns and implications. Nature Reviews Genetics 13:97-109

Gannett L (1999) What's in a Cause? The Pragmatic Dimensions of Genetic Explanations. Biology and Philosophy 14:349-374

Gehring WJ (1998) Master control Genes in development and Evolution: The Homeobox Story. Yale University Press, New Haven, CT

Godfrey-Smith P (2000a) On the Theoretical Role of "Genetic Coding". Phil Sci 67:26-44

Godfrey-Smith P (2000b) Explanatory Symmetries, Preformation, and Developmental Systems Theory. Philosophy of Science 67 (Proceedings):S322-S331

Grice P (1957) Meaning. The Philosophical Review 66:377-388

Griffiths PE, Gray RD (2005) Discussion: three ways to misunderstand developmental systems theory. Biology and Philosophy 20:417-425

Griffiths PE (2001) Genetic Information: A Metaphor in Search of a Theory. Phil Science 68:394-412

Griffiths PE, Knight RD (1998) What is the Developmentalist Challenge?. Philosophy of Science 65:253-258

Griffiths PE, Gray R (1994) Developmental Systems and Evolutionary Explanation. J Phil 91:277-304

Judson HF (1979) The Eighth Day of Creation. Simon & Schuster, New York

Kitcher PS (2001) Battling the Undead: How and How Not to Resist Genetic Determinism. In: Singh RS, Krimbas CB, Paul DB, Beatty J (eds) Thinking about Evolution: Historical, Philosophical, and Political Perspectives. Cambridge University Press, Cambridge, pp 396-414

Maynard Smith J (2000) The Concept of Information in Biology. Phil Sci 67:177-194

Millikan RG (2004) The Varieties of Meaning. MIT Press, Cambridge, MA

Morgan HD, Sutherland HG, Martin DI, Whitelaw E (1999) Epigenetic inheritance at the agouti locus in the mouse. Nature Genetics 23:314-318

Moss L (2003) What Genes Can't Do. MIT Press, Cambridge, MA

Moss L (1992) A kernel of truth? On the reality of the genetic program. PSA 1992: Philosophy of Science Association (Proceedings) 1:335-348

Nirenberg MW, Matthaei HJ (1961) The dependence of cell-free protein synthesis in *E. coli* upon naturally occurring or synthetic polyribonucleotides. Proceedings of the National Academy of Sciences 47:1588-1602

Nishimura S, Jones D. S., Khorana HG (1965) Studies on Polynucleotides. XLVIII. The *in vitro* synthesis of a co-polypeptide containing two amino acids in alternating sequence dependent upon a DNA-like polymer containing two nucleotides in alternating sequence. Journal of Molecular Biology 13:302-324

Northcott R (2009) Is actual difference making actually different?. Journal of Philosophy 106:629-634

Oyama S (2000) Causal Democracy and Causal Contributions in Developmental Systems Theory. Philosophy of Science 67 (Proceedings):S332-S347

Oyama S (1985) The Ontogeny of Information. Cambridge University Press, Cambridge

Robert JS (2004) Embryology, Epigenesis, and Evolution. Cambridge University Press, Cambridge

Sarkar S (2003) Genes Encode Information for Phenotypic Traits. In: Hitchcock C (ed) Contemporary Debates in Philosophy of Science. Blackwell, London, pp 259-272

Scarantino A, Piccinini G (2010) Information without truth. Metaphilosophy 41:313-330

Schaffner K (1998) Genes, behavior, and developmental emergentism: one process, indivisible?. Philosophy of Science 65:209-252

Seong K, Li D, Shimizu H, Nakamura R, Ishii S (2011) Inheritance of Stress-Induced, ATF-2-Dependent Epigenetic Change. Cell 145:1049-1061

Shea N (2011) Developmental systems theory formulated as a claim about inherited information. Philosophy of Science 78:60-82

Shea N (2007a) Representation in the Genome and in Other Inheritance Systems. Biology and Philosophy 22:313-331

Shea N (2007b) Consumers need information: supplementing teleosemantics with an input condition. Philosophy and Phenomenological Research 75:404-435

Stegmann UE (2012) Causal control and genetic causation. Noûs. [Online First DOI: 10.1111/j.1468-0068.2012.00867.x]

Stegmann UE (2009) DNA, Inference and Information. Brit J Phil Sci 60:1-17

Stegmann UE (2005) Genetic information as instructional content. Phil Sci 72:425-443

Sterelny K (2000) The "Genetic Program" Program: A Commentary on Maynard Smith on Information in Biology. Phil Sci 67:195-201

Sterelny K, Griffiths PE (1999) Sex and Death: An Introduction to Philosophy of Biology. University of Chicago Press, Chicago

Sterelny K, Smith K, Dickison M (1996) The Extended Replicator. Biol Phil 11:377-403

Stotz K (2006) With 'Genes' like That, Who Needs an Environment? Postgenomics's Argument for the 'Ontogeny of Information'. Philosophy of Science 73:905-917

Waters CK (2007) Causes that make a difference. Journal of Philosophy 104:551-579

Waters CK (2006) The Pluralist Stance. Minnesota Studies in Philosophy of Science 19:7-29

Weber M (forthcoming) Causal selection vs causal parity in biology: relevant counterfactuals and biologically normal interventions. Minnesota Studies in Philosophy of Science

Weber M (2005a) Philosophy of Experimental Biology. Cambridge University Press, Cambridge

Weber M (2005b) Genes, causation and intentionality. Hist Phil Life Sci 27:399-411

Woodward J (2010) Causation in biology: stability, specificity, and the choice of levels of explanation. Biology and Philosophy 25:287-318

Woodward J (2003) Making things happen: a theory of causal explanation. Oxford University Press, New York