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The inheritance of features

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Abstract. Since the discovery of the double helical structure of DNA, the standard account of the inheritance of features has been in terms of DNA-copying and DNA-transmission. This theory is just a version of the old theory according to which the inheritance of features is explained by the transfer at conception of some developmentally privileged material from parents to offspring. This paper does the following things: (1) it explains what the inheritance of features is; (2) it explains how the DNA-centric theory emerged; (3) it clarifies the relation between the DNA-centric theory and the 'unfolding' theory of development; (4) it argues that (given what we now know about developmental processes and genetic activity) the DNA-centric theory should be abandoned in favour of a pluralistic (but not holistic) theory of the inheritance of features. According to this pluralistic theory, the reliable reoccurrence of phenotypes must be explained by appealing not only to processes responsible for the reliable reoccurrence of genetic developmental factors but also to processes responsible for the reliable reoccurrence (or persistence) of nongenetic developmental factors.

Introduction

This paper is about the inheritance of features: it is about the *concepts* that can be used to understand this process and about the *theories* that can be used to explain it. Since the discovery of the double helical structure of DNA, the standard account of the inheritance of features has been in terms of DNA-copying and DNA-transmission. I call this theory the *DNA-centric theory of the inheritance of features*. This theory is just a version of the old view according to which the inheritance of features is explained by the transfer of some developmentally privileged material from parents to offspring that occurs at conception. I call this more general theory the *conception/donation theory of the inheritance of features*.

The paper is organized as follows. The next three sections deal with some important preliminary matters and explain what the inheritance of features consists in: the inheritance of features is the process that explains the *like-begets-like phenomenon*. The following three sections tell how the DNA-centric version of the conception/donation theory emerged from previous versions of this theory. Then there are two sections that spell out the relation between the DNA-centric theory (and more generally the conception/donation theory) and the *unfolding theory of development*. The last two

sections show why we need to abandon the DNA-centric theory (and more generally the conception/donation theory) in favour of a pluralistic (but not holistic) theory of the inheritance of features. The inheritance of features can be properly explained only by appealing to processes that have to do with the persistence of environmental conditions and with the reliable reoccurrence of nongenetic developmental factors; DNA-copying and DNA-transmission are not enough.

Preliminary distinctions

In order to reduce to a manageable size the considerations I want to present, I need to make some preliminary distinctions. The first distinction is between vertical and horizontal inheritance. *Vertical inheritance* is a causal process that involves only entities belonging to the same biological lineage. *Horizontal inheritance* is a causal process may (and usually does) involve entities belonging to different biological lineages.[1]

The second distinction is between upward and downward inheritance. *Downward inheritance* is a causal process where the causal arrow goes from the older to the younger entities. *Upward inheritance* is a causal process where the causal arrow goes from the younger to the older entities. This distinction cuts across the vertical/horizontal distinction. For example, some authors have a special name for downward horizontal inheritance: they call it *oblique inheritance* or oblique transmission (Cavalli Sforza and Feldman 1981).

The third distinction is between inheritance at the level of the individual organism (*individual-level inheritance*) and inheritance at some other level of the biological hierarchy (*nonindividual-level inheritance*). Nonindividual-level inheritance is a heterogeneous category that includes both sub-individual and super-individual inheritance processes. *Sub*-individual-level inheritance is inheritance that involves biological entities that are smaller than individual organisms, e.g. the cells of a multicellular organism. *Super*-individual-level inheritance is inheritance that involves biological entities that are bigger than individual organisms, e.g. groups of organisms, species, ecosystems, etc. The distinction between individual-level and nonindividual-level inheritance cuts across each of the two previous distinctions. It is possible in principle to have vertical and horizontal inheritance and upward and downward inheritance at each level of the biological hierarchy.

[1]Two entities belong to the same biological lineage only if one of the two entities is a biological ancestor of the other entity. An entity e_1 is a biological ancestor of another entity e_2 only if e_1 is a biological parent of e_2 or e_1 is the biological parent of an entity e_{1*} which in turn is a biological ancestor of e_2 (recursive definition).

Given these distinctions, there are at least 12 ($2 \times 2 \times 3$) possible kinds of inheritance. I will focus on one kind only: *downward vertical individual-level inheritance*. Why? This kind of inheritance is the most familiar of all; it is the kind of inheritance people usually refer to when they talk about inheritance. Moreover, it is usually thought that this kind of inheritance is the most biologically significant. Many authors agree that in principle it is possible to have horizontal or upward inheritance, or inheritance at some level other than the level of the individual organism, but only few think that these kinds of inheritance processes are biologically significant. I happen to be one of those who think that the nonstandard kinds of inheritance processes are of great biological significance. But in this paper I will not be concerned with the nonstandard kinds of inheritance, even though some of the considerations I will make can be applied to some of the nonstandard cases too.

Inheritance of features and differences

There is another distinction I need to introduce. It is the distinction between the inheritance of features and the inheritance of differences. In discussions of biological matters, the phrases 'inheritance of traits', 'inherited traits' and 'heritable traits' occur very often. But it is important to understand that these phrases are ambiguous. Their ambiguity is due primarily to the ambiguity of the word 'trait'. This word can be used to refer to a particular biological feature or it can be used to refer to some possible dimension of similarity of dissimilarity. In the first sense, 'trait' refers to things like: the property of having four limbs, the property of being 176 cm tall, the property of having a pointed nose, etc. In the second sense, 'trait' refers to things like: number of limbs, height, shape of nose, etc. We can say that 'trait' can be used to refer to a particular value (being 176 cm tall) as well as to sets of possible values (height).

When the word 'trait' is used to refer to features (specific values), 'inheritance of trait', 'inherited traits' and 'heritable traits' are simply synonymous, respectively, with 'inheritance of features', 'inherited features' and 'heritable features'. In contrast, when 'trait' is used to refer to dimensions of similarity, 'inheritance of a trait' is synonymous with 'inheritance of the variation for a trait in a given population at a given time'. And, similarly, when 'trait' is used in this sense, 'inherited trait' is synonymous with 'inherited variation for a trait in a given population at a given time' and 'heritable trait' is synonymous with 'heritable variation for a trait in a given population at a given time'.

All this means that there are two different sets of inheritance concepts. The first has to do with features and comprises:

1.1 The concept of the inheritance of features (*the concept of inheritance*$_{\mathrm{F}}$);
1.2 The concept of inherited feature (*the concept of inherited*$_{\mathrm{F}}$);

1.3 The concept of heritable feature (*the concept of heritable*$_F$).

I will call these three concepts the *inheritance*$_F$ *concepts*. The second set of concepts has to do with variation (that is, with differences) and comprises:

2.1 The concept of the inheritance of variation (*the concept of inheritance*$_V$);
2.2 The concept of inherited variation (*the concept of inherited*$_V$);
2.3 The concept of heritable variation (*the concept of heritable*$_V$).

I will call these three concepts the *inheritance*$_V$ *concepts*. In this paper, I will talk only about the inheritance$_F$ concepts. The relation between inheritance$_F$ and inheritance$_V$ is a very important topic and the misunderstanding of this relation has played a very important role in the history of the theories of inheritance. But my focus here is exclusively on inheritance$_F$. (I have explored some aspects of the relation between the inheritance of features and the inheritance of differences in Mameli 2004).

The like-begets-like phenomenon

The inheritance$_F$ concepts can be clarified by explaining their relation to what I will call the *like-begets-like phenomenon*. The like-begets-like phenomenon is something the existence of which human beings – and human breeders in particular – have known for a long time. It is simply the fact that biological organisms (through reproduction) generate organisms with features that are the same as (or similar to) those of the organisms that have generated them. So, four-legged organisms (usually and reliably) beget four-legged organisms; two-eyed organisms (usually and reliably) beget two-eyed organisms; fast-running organisms (usually and reliably) beget fast-running organisms; etc. The like-begets-like phenomenon does not apply to all features of all organisms. But it applies to many important features of all organisms and, for this reason, it is one of the most important facts about the biological world.

The concept of inheritance$_F$ functions to refer to the intergenerational process or processes that explain the like-begets-like phenomenon. Within each biological lineage, there are features that usually and reliably reappear generation after generation. That is, for each biological lineage, there exist reliable within-lineage similarities. The concept of inheritance$_F$ refers to the intergenerational process or processes that explain this reliable reoccurrence of features within lineages.

The concept of inherited$_F$ and the concept of heritable$_F$ refer to features of organisms to which the like-begets-like phenomenon applies, i.e. those features of organisms that reliably reoccur within lineages. The difference between the two concepts is that the concept of inherited$_F$ is backward looking, while the concept of heritable$_F$ is forward looking. A feature of an organism is inherited$_F$ if its occurrence in that organism can be explained by the occurrence of an inheritance$_F$ process that connects that organism with its parents. In contrast, a

feature of an organism is heritable$_F$ if it is likely that the offspring of that organism will have that feature as a result of an inheritance$_F$ process that connects them with their parent. That is, a feature of an organism is heritable$_F$ if it has the capacity of being inherited$_F$ by the organism's offspring.

The conception/donation theory

The inheritance$_F$ concepts are commonsense concepts. Human beings have known for a long time of the existence of many reliable similarities between parents and offspring. Therefore, for an equally long time, they must have had a concept that refers to the processes – whatever they are – responsible for these reliable similarities. And they must have had concepts that refer (either in a backward-looking way or in a forward-looking way) to the features that reliably reoccur within lineages thanks to these processes. In contrast, the inheritance$_V$ concepts are recent technical concepts. They were introduced by Darwin and they are essentially related to Darwinian population thinking. But, as said, I will not talk about these concepts in this paper.

The like-begets-like phenomenon is discussed in some of the oldest scientific treatises about biological matters. For example, Hippocrates (c.460–c.370 B.C.) discussed it in *On Generation* and in *On Airs, Waters and Places*. And Aristotle (388–322 B.C.) discussed it in *On the Generation of Animals* and in *On the History of Animals*. This is what Hippocrates wrote:

> If, then, children with bald heads are born to parents with bald heads; and children with blue eves to parents who have blue eyes; and if the children of parents having distorted eyes squint also for the most part; and if the same may be said of other forms of the body, what is to prevent it from happening that a child with a long head should be produced by a parent having a long head? (*On Airs, Waters and Places*, part 14, translation by F. Adams)

Hippocrates and Aristotle not only noticed that the like-begets-like phenomenon occurs but they also tried to provide an explanation for it. Their theories differ in many important details: Hippocrates believed in the contribution of both parents, while Aristotle thought that the like-begets-like phenomenon was due entirely to the forming action of male semen; Hippocrates believed in a version of what Darwin (1868, 1869, 1871a, 1871b) subsequently called 'pangenesis', while Aristotle did not; etc. But there are some features that the two theories have in common. According to both theories, the like-begets-like phenomenon can be explained by appealing exclusively to what happens at the moment of conception. At conception, the sexual substances of males and females (what we now call 'gametes') meet, fuse and a new organism is formed. The sexual substances (at least those of one of the parents) carry within themselves some material, or principle, or factor that becomes part of the new organism and causes it to have (at conception) or acquire (after conception)

some of the parental features, including both features that the parents share with the other individuals in their species and features that are specific to the parents. What happens is that the parents at conception 'donate' to their offspring some developmentally important material that causes the offspring to develop in such a way as to resemble the parents. I will call *conception/donation theories* all the theories of the like-begets-like phenomenon that have this structure.

With very few exceptions, all the theories of the like-begets-like phenomenon ever formulated are of the conception/donation kind. For example, both the 17th century supporters of the theory of preformation and the 17th century supporters of the theory of epigenesis held a conception/donation view. The disagreement was about the nature of the material donated by parents to offspring at conception and not about the fact that the like-begets-like phenomenon had to be explained by the transfer of this material from parents to offspring. According to the supporters of preformation, the material transmitted from parents to offspring in the sexual substances was constituted by miniature versions of organisms and features; according to the supporters of epigenesis it was not. But the supporters of the two theories agreed about the fact that the crucial elements for the explanation of the like-begets-like phenomenon were to be found in the sexual substances (Pinto Correia 1997; Benson 2002).

Another example comes from the comparison of the theories of the like-begets-like phenomenon formulated by Lamarck, Darwin and Weismann. All three held a conception/donation theory of the like-begets-like phenomenon. Their disagreement was about whether the like-begets-like phenomenon extended to new idiosyncratic features that organisms acquire during their life or not. Lamarck (in his *Philosophie Zoologique*, 1809) and Darwin (1868, 1869, 1871a, 1871b) thought that it did. Weismann (1892, 1889) thought that it did not. Darwin tried to give a mechanistic explanation of how the like-begets-like phenomenon could apply to 'acquired characters'; this is his famous theory of 'pangenesis'. Weismann argued that pangenesis could not possibly occur. But there was no disagreement about the conception/donation theory. In fact, both Darwin's and Weismann's arguments *presuppose* the conception/donation theory and would not make sense in a context where the conception/donation theory is not taken for granted. In order to argue that the like-begets-like phenomenon applies to 'acquired characters', Darwin argued that such characters could be passed on to the offspring in this way: the 'acquired characters' produce 'gemmules', the gemmules are transferred to the offspring at conception, and they cause the development in the offspring of features similar to those by which the gemmules have been produced in the parents. Darwin was assuming that only a mechanism that explains the transfer of acquired parental features through the transfer at conception of some special substance could be scientifically acceptable. Similarly, in order to argue that the like-begets-like phenomenon does *not* apply to the case of acquired parental features, Weismann claimed that nothing like the Darwinian gemmules could exist. From this he inferred that acquired parental features could not be passed on to the offspring through the transfer of some substance at conception. And from

this he inferred that no mechanism for passing on these features could exist. He was assuming that if a feature cannot be passed on through a conception/donation kind of mechanism, then it cannot be passed on at all, i.e. it cannot be subject to the like-begets-like phenomenon.

The metaphor of inheritance

Since the conception/donation theory is a theory that tries to explain the like-begets-like phenomenon, and since the concept of inheritance$_F$ is that concept that refers to the processes (whatever they are) that explain the like-begets-like phenomenon, it follows that the conception/donation theory is a theory of inheritance$_F$. The conception/donation theory was until very recently the only game in town as an explanation of the like-begets-like phenomenon. This fact is crucial for understanding why the word 'inheritance' got associated with the processes responsible for the like-begets-like phenomenon, i.e. why 'inheritance' ended up being used to express the concept of inheritance$_F$.

Words like 'inheritance', 'inherited', 'heredity', 'hereditary', and 'heritable' have their origin in the social context and they refer to things that have to do, in the first instance, with the transfer of property or wealth from parents to offspring. The use of these words in the biological context was originally a metaphorical use. Human offspring inherit the property (wealth) of their human parents. In the same way, all biological offspring inherit some of the properties (features) of their biological parents. In the social context, 'inheritance' refers to the process by which offspring acquire their parents' possessions and in the biological context it can be used to refer to the process by which organism acquire their parents' features. I will call this the *metaphor of inheritance*.

The metaphor of inheritance is now almost a dead metaphor and, thereby, we barely notice it. But it is important to realize that 'inheritance' and similar words were not always used to talk about the explanation of the like-begets-like phenomenon. Hippocrates and Aristotle talked about the like-begets-like phenomenon and tried to describe the process responsible for this phenomenon, but they never used the metaphor of inheritance. They never, in this context, used words that are the ancient Greek equivalents of 'inheritance', 'inherited', 'heredity', 'hereditary', and 'heritable'.

When were these words first used in this context? When was the metaphor of inheritance first formulated? This is an interesting historical question that seems to have received very little attention from historians. The phrase 'the metaphor of inheritance' appears in Sapp (2003b: p. 134). Sapp suggests that it was Darwin – in *On the Origin of Species* (1859) – to introduce this metaphor in biology. Unsatisfied with this suggestion, I decided to look at the online edition of the Oxford English Dictionary (OED).

The earliest occurrence reported by the OED of the verb 'to inherit' being used to talk about the like-begets-like phenomenon is in Shakespeare's play *Henry IV* (Part II), composed around 1597. This play contains the following lines:

> […] Hereof
> comes it, that Prince *Harry* is valiant: for the cold blood
> hee did naturally inherite of his Father, hee hath, like
> leane, stirrill, and bare Land, manured, husbanded, and
> tyll'd, with excellent endeauour of drinking good, and
> good store of fertile Sherris, that hee is become very hot,
> and valiant. […] (Act IV, scene iii).

Shakespeare must have liked the metaphor as he used it again four years later (1601) in *All's Well That Ends Well*:

> Youth, thou bear'st thy Fathers face,
> Franke Nature rather curious then in hast
> Hath well compos'd thee: Thy Fathers morall parts
> Maist thou inherit too […] (Act I, scene ii).

Shakespeare also used the adjective 'hereditary' in connection with the like-begets-like phenomenon. For example, in *Antony and Cleopatra* (composed around 1606) he wrote:

> His faults in him, seeme as the Spots of Heauen,
> More fierie by nights Blacknesse; Hereditarie,
> Rather then purchaste: what he cannot change,
> Then what he chooses. (Act I, scene iv).

The earliest occurrence of the word 'hereditary' in a biological context is, according to the OED, in a work by the composer Thomas Morley. In his treatise, *A Pleine and Easie Introduction to Practicall Musicke*, published in 1597, the phrase 'hereditary lepresie' (163) occurs.

Despite the fact that the verb 'to inherit' had been used in connection with the like-begets-like phenomenon by Shakespeare in 1597, the earliest occurrences reported by the OED of the noun 'inheritance' being used in connection with the like-begets-like phenomenon are in the first edition of Darwin's *Origin*. This is where Sapp's suggestion that the metaphor of inheritance is due to Darwin comes from (Sapp, personal communication). In chapter 1 of the *Origin*, Darwin writes: 'No breeder doubts how strong is the tendency to inheritance: like produces like is his fundamental belief: doubts have been thrown on this principle by theoretical writers alone.' In chapter 4, while talking about the features shared between species, he writes: '[These] characters in common I attribute to inheritance from a common progenitor'. And many other examples can be found in this book.[2]

[2]Darwin did not use the word 'inheritance' in its biological sense in the writings that preceded the first edition of the *Origin*. This includes Darwin's narrations of the voyage of the Beagle (Darwin 1845) and Darwin's first presentation of the theory of natural selection (Darwin and Wallace 1858). But, in Darwin (1845: ch. 8, 10, 17) the adjectives 'inherited' and 'hereditary' are used to talk about 'instincts', 'habits' and 'structures'. In Darwin and Wallace (1858: p. 49) the words 'inherited', 'inherit' and 'inheriting' appear in the section written by Darwin, but not in the one written by Wallace.

Similarly, despite the fact that the adjective 'hereditary' had been used in connection with the like-begets-like phenomenon by Morley in 1597, the earliest occurrences reported by the OED of the noun 'heredity' being used in a biological context are in Herbert Spencer's *Principles of Biology* (1863: sections 80 and 82) and in Francis Galton's *Hereditary Genius* (1869: p. 334).[3]

Shakespeare and Morley were not the first writers to use the metaphor of inheritance though. Two quotes are given in the OED, one from a work composed in 1570 and another from a work composed in 1571, where the word 'heritable' is used metaphorically to talk about features that are 'naturally transmissible from parents to offspring'. The first quote is the following: 'Arrogance, crueltie, dissimulatioun, and heretabill tressoun.' It is from a document written by titled *Ane Admonition Direct to the Trew Lordis Mantenaris of Kingis Graces Authoritie*, written by the Scottish humanist George Buchanan in 1570. The second quote is this: 'Sinne floweth by infection intoo the offspring, and is as it were heritable.' This quote is from Arthur Golding's 1571 English translation of John Calvin's *Commentaries on Psalms*. Did Golding introduce the metaphor in the translation? Or was the metaphor present in the original? And if it was present in the original, did the metaphor originate in Calvin's mind or did it come from somewhere else?

I leave these questions to the historians. But even more interesting than the question about *when* the metaphor of inheritance was introduced is the question about *why* it was introduced. Here is what I think the answer to this question is. Given that the conception/donation theory was (and for such a long time) the only available explanation of the like-begets-like phenomenon, it became natural to think of the process responsible for the like-begets-like phenomenon in terms of parents 'giving' something developmentally special to their offspring at conception. And it became natural to think of the features to which the like-begets-like phenomenon applies (i.e. the features that reliably reoccur within lineages) as features that are 'given' to the offspring by the parents by means of what happens at conception. The step from the idea of parents 'giving' (at conception) some developmentally important factors and thereby some features to the idea of the offspring 'inheriting' (at conception) such factors and such features was a small one. It is because of the attractiveness of the conception/donation theory that the metaphor of inheritance was formulated and adopted. And it is because of the plausibility of the conception/donation theory that the metaphor of inheritance became entrenched.

It is in this way that the process responsible for the like-begets-like phenomenon ended up being called 'inheritance'. That is, it is in this way that the word 'inheritance' came to be used to express the concept of $\text{inheritance}_{\text{F}}$. But, for the arguments that follow, it is important to keep in mind the following facts. One can possess the concept of $\text{inheritance}_{\text{F}}$ without having any

[3]An anonymous referee for this journal suggested that, in order to reconstruct the history of the metaphor of inheritance, it may be useful to look at the writings of pre-Mendelian breeders such as J.K. Nestler (1783–1841); see (Oriel 1996).

particular view about the nature of this process and, thereby, about the explanation of the like-begets-like phenomenon. Moreover, one can possess the concept of inheritance$_F$, believe in the truth of some version of the conception/donation theory and not use the word 'inheritance' to express the concept of inheritance$_F$; this, for example, is the case of Hippocrates and Aristotle. Or one can possess the concept of inheritance$_F$ and use the word 'inheritance' to express this concept but hold a view incompatible with a conception/donation theory.

The path to the double helix

Scientific progress is often the result of an effort to combine old theories or old preconceptions with new data obtained with new technologies. This is certainly what happened in the case of theories of the like-begets-like phenomenon in the 18th, 19th and 20th century.

In the second half of the 17th century, *gametic cells* were for the first time observed and described. Regnier de Graaf discovered the ovarian follicles, and thought he had been able to see the mammalian ovum or egg. Around the same time, Antonie Van Leeuwenhoek invented the microscope and for the first time observed the things that we now call 'cells'. Some of the first cells that Van Leeuwenhoek observed were the spermatozoa within male semen. Around the same time, Marcello Malpighi and Jan Swammerdam thought they could see rudiments of adult biological structures in the very early stages of the development of the embryo. The classic preformationist theory was soon formulated and became the preferred view of many materialistic thinkers in the eighteen century (Pinto Correia 1997; Benson 2002). The important thing to note is just the fact that, as soon as gametic cells were discovered, the view was formulated according to which these cells are the vehicles by which organisms 'donate' some of their features to their offspring. The conception/donation theory was in the background: it shaped the way research was conducted and the way the newly acquired knowledge about the microscopic level was assimilated. The new data were not used to test the conception/donation theory; rather, they were used to fill in its details. In this way, a new version of the conception/donation theory was formulated. We can call it the *gametocentric* theory of inheritance$_F$.

In 1866, Ernst Haeckel hypothesized that the developmentally important materials that parents donate to their offspring at conception and that are responsible for the like-begets-like phenomenon are contained in the *nucleus* of gametic cells. In 1876, Oscar Hertwig inferred from a study of the reproduction of the sea urchin that fertilization consists in the union of the two nuclei contributed by the male and female parents. In 1877, Hermann Fol reported observing the spermatozoa of a starfish penetrate the egg and the transfer of the intact nucleus of the sperm into the egg. In the 1880s, the view that the like-begets-like phenomenon is explained by the transfer of nuclei from parents to offspring was defended by many scientists. Eduard Strasburger and August Weismann (1889,

1892; see Farley 1982; see also Johannsen 1911) were among them. Weismann used his ideas about the role of the nucleus to argue that Darwin's Lamarckian mechanism of pangenesis could not exist. Even though some biologists, supporters of the cytoplasmic view of inheritance, resisted Weismann's arguments, the majority was convinced (Sapp 1987, 1994, 2003a, b). Again, the important thing to note is that the newly acquired knowledge about the microscopic level was used to fill in the details of conception/donation theory. It was never used to question this theory. In this way, a new version of the conception/donation theory was formulated: the *nucleocentric* theory of inheritance$_F$.

Something analogous occurred in the next stage of 'the path to DNA' (Olby 1994). In 1900, Mendel's results (Mendel 1865) were rediscovered and biologists started thinking about how to make sense of those results at the molecular level. In the first decades of the 20th century, Thomas Hunt Morgan and his colleagues developed what we can call the *chromosomecentric* theory of inheritance$_F$, a new version of the conception/donation theory (Morgan 1909, 1910, 1919; Morgan et al. 1915). On this view, it is not the whole nucleus that is important for the like-begets-like phenomenon. The developmentally special stuff responsible for reliable parent-offspring similarities is contained in some special nuclear structures, the chromosomes. Morgan's studies with flies provided more data to fill in more details of the conception/donation theory.

The next important stage was the formulation of the theory that, in so far as the like-begets-like phenomenon is concerned, one should not focus on the whole chromosome, but only on its DNA component. This is what many scientists took Avery et al. (1944) to have shown. The transfer of DNA from parents to offspring became, in the mind of many biologists, the only process responsible for the like-begets-like phenomenon. The chromosomecentric theory of inheritance$_F$ became the *DNA-centric* theory of inheritance$_F$, yet another version of the conception/donation theory.

The DNA-centric theory was not fully accepted for some time. How could parent-to-offspring DNA-transfer give rise to the like-begets-like phenomenon? The solution was given by Watson and Crick's discovery of the double-helical structure of DNA (Watson and Crick 1953a, 1953b). Given its structure, DNA seemed to many to be perfectly suited to play the role of the inherited developmentally special stuff responsible for the like-begets-like phenomenon. The combinatorial nature of DNA and its length meant that DNA could be complex enough to determine and direct development in all its specific aspects. And the simplicity of DNA's semi-conservative mode of replication meant that DNA-copying and DNA-transmission could be reliable and direct and, thereby, that they could explain the many reliable similarities between parents and their offspring. DNA-copying and DNA-transmission could explain the like-begets-like phenomenon. No appeal to any other process was needed. This is how John Maynard Smith famously put it:

> Although it is a big step from the discovery that the transforming factor in bacteria is DNA [i.e. from the discovery of Avery and colleagues] to

> the assumption that all genes are simply molecules of DNA, this step has been taken by most biologists. The reason for this ready conversion is interesting. It would be difficult to prove that genes cannot be made of substances other than DNA. But the structure of DNA explains both specificity and replication, and [...] it also explains how genes can influence development. It seems unlikely that another class of molecule able to combine these properties will be discovered and, therefore, natural to leap to the conclusion that all genes in all organisms are made of DNA (or at least of nucleic acid; a related molecule, RNA, can have gene-like properties). (Maynard Smith 1993: 72; see also Dawkins 1999, 1986, 1996; Bowler 2003)

In addition to the discovery of the double helical structure of DNA, there was also the discovery of the processes of transcription and translation and of what Crick (1958, 1970) called the 'Central Dogma' of molecular biology – i.e. the fact that reverse translation does not occur. This discovery matched what Weismann had said about pangenesis: the mechanism hypothesized by Darwin did not exist (Maynard Smith 1993, 1998; Dawkins 1999). More details of the 'true' version of the conception/donation theory were being uncovered.

Watson and Crick's discovery and what were thought of as its obvious implications for the theory of inheritance started to become popular. Today, the DNA-centric theory of inheritance$_F$, i.e. the DNA-version of the conception/donation theory, is the received view about inheritance$_F$. And this is true not only for scientists but for lay people as well. The DNA-centric theory is a cornerstone of scientific biology. The conception/donation theory of inheritance$_F$ has evolved through the ages: from the pre-microscope versions of Hippocrates, Aristotle and others, to the gametocentric versions of the 18th century, to the nucleocentric versions of the 19th century, to the chromosomecentric versions of the first half of the 20th century, to the DNA-centric versions of the second half of the 20th century. The details have changed, but the basic assumptions have not. On the contrary, the basic assumptions have driven and shaped the process of scientific discovery. These assumptions have led to many important discoveries. In spite of this, they need to be questioned.

The assumptions of the DNA-centric theory

The aim of this section is to clarify the DNA-centric theory of inheritance$_F$. According to this theory, all that is needed in order to explain the like-begets-like phenomenon is DNA-copying and DNA-transmission. On this view, DNA-copying and DNA-transmission are *explanatorily sufficient* for the reliable reoccurrence of biological features within lineages. The DNA-centric theory is supposed to apply to all genetic and phenotypic features that reliably reoccur within lineages with one exception. The exception is given by reliably

reoccurring 'cultural' phenotypes. On the DNA-centric theory, cultural phenotypes that reliably reoccur do so not only because of DNA-copying and DNA-transmission but also because of cultural copying and cultural transmission. This idea was the motivation for the elaboration of dual-inheritance theories (Cavalli Sforza and Feldman 1981, 2002; Boyd and Richerson 1985, 1996, 2000; Laland et al. 1996b; Durham 1991; Cavalli Sforza 2001; see also Laland 2002; Laland and Brown 2002) and also prompted some attempts to develop a theory of 'memes' (Dawkins 1989, 1983; Dennett 1995, 2001a, b; see also Wimsatt 1999; Aunger 2000, 2003). In this paper, I will not deal with issues concerning cultural inheritance.

Let F be a *noncultural* genetic or phenotypic feature that reliably reoccurs (i.e. is inherited$_F$) in a lineage. How can DNA-copying and DNA-transmission be sufficient to explain the reliable reoccurrence (the inheritance$_F$) of F? One possible account is the following. DNA-copying and DNA-transmission can be explanatorily sufficient for the reliable reoccurrence of F if having F is nothing but having certain DNA molecules. If the possession of F consists in the possession of certain DNA sequences, then DNA-copying can generate new tokens of F and DNA-transmission can bring about that these new tokens are injected into the offspring at conception.

If F is a *genetic* feature, the account just given seems correct. On the current understanding of what genes are, the possession of a given genetic feature is equivalent to the possession of a given DNA sequence or a given set of DNA sequences. Thereby, DNA-copying can produce new tokens of genetic features and DNA-transmission can cause these new tokens to be transferred to the offspring at conception. It is for this reason that DNA-copying and DNA-transmission can be said to be sufficient to explain the reliable reoccurrence of genetic features.

In contrast, if F is a *phenotypic* feature, the account just given cannot be correct. Phenotypes are the result of developmental processes. New tokens of phenotypes cannot be generated by means of DNA-copying only; and they cannot be transferred from parents to offspring by means of DNA-transmission only. Let F be a noncultural *phenotypic* feature that reliably reoccurs in a lineage. How could DNA-copying and DNA-transmission be seen as sufficient to explain the reliable reoccurrence (the inheritance$_F$) of F? DNA-copying and DNA-transmission can be seen as explanatorily sufficient for the reliable reoccurrence of F if and only if DNA molecules are explanatorily sufficient for the development of F.

Let us suppose that the development of phenotype F in an organism *can* be explained by appealing only to the presence of a set of genes G in that organism and to the interactions among these genes. If this is so, the reliable reoccurrence of F in a lineage can be explained by appealing exclusively to the reliable reoccurrence of G in that lineage. And the reliable reoccurrence of G in the lineage can be explained by appealing exclusively to the occurrence of DNA-copying and DNA-transmission in that lineage. In other words, if genes are explanatorily sufficient for the development of phenotypes, the problem of

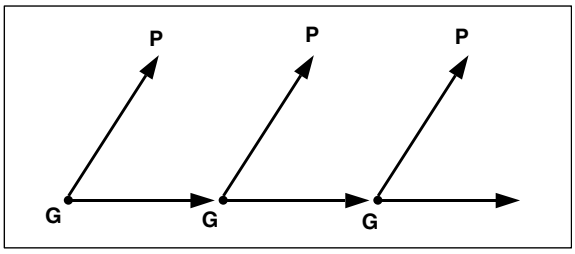

Figure 1. The Dna-centric theory of the inheritance of features.

explaining the reliable reoccurrence (inheritance_F) of phenotypes can be *reduced* to the problem of explaining the reliable reoccurrence (inheritance_F) of genetic features; and this problem can be solved by appealing to DNA-copying and DNA-transmission.

Let us suppose instead that the development of phenotype F in an organism *cannot* be explained by appealing only to the presence in the organism of certain genes and to the interactions among them. Genes are not explanatorily sufficient for the development of F: an explanation of F's development must mention a set of genes G as well as a set of environmental factors E. If this is so, the reliable reoccurrence of F in a lineage cannot be explained by appealing exclusively to the reliable reoccurrence of G in that lineage and thereby it cannot be explained by appealing exclusively to the occurrence of DNA-copying and DNA-transmission in that lineage. If E is needed to explain the development of F, then the reliable reoccurrence of E is needed to explain the reliable reoccurrence of F. In other words, if genes are not explanatorily sufficient for the development of phenotypes, the problem of explaining the reliable reoccurrence (inheritance_F) of phenotypes cannot be *reduced* to the problem of explaining the reliable reoccurrence (inheritance_F) of genetic features and, thereby, DNA-copying and DNA-transmission cannot be enough.

The DNA-centric theory is supposed to apply to *all* reliably reoccurring (inherited_F) noncultural phenotypes. Thus, for what said above, the DNA-centric theory entails that all reliably reoccurring (inherited_F) noncultural phenotypes are such that genetic features are explanatorily sufficient for their development. On the DNA-centric theory of inheritance_F, the inheritance_F of noncultural phenotypic features is explained by the inheritance_F of genetic features and by nothing else. Apart from cultural transmission, the concept of inheritance_F refers only to DNA-copying and DNA-transmission; and the concepts of heritable_F and inherited_F refer only to genetic features and to phenotypic features whose development can be explained in purely genetic terms. A standard way of representing this theory graphically is what is known as *Weismann's diagram* (Figure 1).[4]

[4]This diagram is adapted from Maynard Smith (1993, 1998). The diagram in Weismann (1892) is different in some important respects.

The assumptions of the conception/donation theory

The DNA-centric theory is just one version of the conception/donation theory. According to the DNA-centric theory it is DNA that, by being transferred from parents to offspring at conception, explains the like-begets-like phenomenon. In contrast, the conception/donation theory in its general form is neutral with respect to the nature of the factors that, by being transferred from parents to offspring at conception, explain the like-begets-like phenomenon. The conception/donation theory in its general form only says that such factors exist.

I will call *conceptional* all the features an organism has at conception, i.e. at the moment it starts existing. Thanks to the transfer of DNA molecules from parents to offspring, at conception an organism already has many genetic features. A genetic feature may consist in having gene A at locus α and gene B at locus β. Parentally derived genetic features are conceptional features but not all the conceptional features of an organism are genetic.[5] The parent-to-offspring material transfer that occurs at conception involves more than DNA. Today, we know that it involves membranes, cytoplasm, proteins, RNA compounds of various kinds, etc. All organisms (except viruses) start their life not as DNA-molecules, but as cells. And in virtue of their parentally derived non-DNA cellular constituents, organisms have many nongenetic conceptional features. An example could be the feature of having a given RNA compound in a given section of the zygote.

Like all other features, conceptional features can be intrinsic or relational. The conceptional features I have mentioned so far are all *intrinsic*: they depend only on the organism in question having certain kinds of cellular constituents, cellular constituents that the organism has 'received' from its parents at conception. But obviously organisms have *relational* conceptional features too. An example could be the feature of being located in given section of one's mother's womb at the moment of conception. The possession of relational features depends (at least in part) on things other than one's own cellular constituents.

Since both the DNA-centric theory and the conception/donation theory are supposed to apply to all phenotypes except for those influenced by culture, in what follows, I will use the word 'phenotype' to refer to noncultural phenotypes only. In the same way that we asked about how the DNA-centric theory can be applied to phenotypes, we can also ask about how the conception/donation theory in its general form can be applied to phenotypes. We saw that the DNA-centric theory can be applied to phenotypes only on the assumption that genetic features are explanatorily sufficient for the development of reliably reoccurring phenotypes. Something analogous holds for the conception/donation theory in its general form. The conception/donation theory can be

[5]Organisms can have also genetic features that are not conceptional. These are genetic features due to mutations and copying mistakes that occur within the organisms during its life, e.g. in cancerous cells.

applied to phenotypes only on the assumption that intrinsic conceptional features (genetic and/or nongenetic) are explanatorily sufficient for the development of reliably reoccurring phenotypes. The parent-to-offspring material transfer occurring at conception is (usually) sufficient to explain the intrinsic conceptional features of an organism. If it is true that this material transfer is sufficient to explain the reliable reoccurrence of phenotypes within lineages, then it must be the case that intrinsic conceptional features are sufficient to explain the development of these phenotypes.

Lewontin (1993, 2000) reminds us that the use of the word 'development' to talk about the biological process of organic development is metaphorical. He calls it the *metaphor of development*: 'development' means 'unfolding'. When we use the word 'development' to talk about the causal process that goes from the intrinsic conceptional features of an organism to its phenotypes – from zygote to adult – we are somehow suggesting that this process is like an unfolding: phenotypes are seen as resulting from an unfolding of what is present in the zygote. And, in the jargon that I have used so far, this is like saying that the zygote is seen as explanatorily sufficient for the emergence of phenotypes.

The conception/donation theory can be applied to reliably reoccurring phenotypes only on the assumption that the metaphor of development is an accurate metaphor for describing the process that generates these phenotypes. That is, the metaphor of inheritance – or to be precise, the metaphor of *inheritance at conception* – is accurate only in so far as the metaphor of development is accurate for (at least) reliably reoccurring ($\text{inherited}_{\text{F}}$) phenotypes.

All versions of the conception/donation theory are committed to a version of the *unfolding theory of development*. But different versions of the conception/donation theory are committed to different versions of the unfolding theory. The DNA-centric theory is committed to the idea that $\text{inherited}_{\text{F}}$ phenotypes can be seen as unfolding from genetic features. The nucleocentric theory is committed to the idea that $\text{inherited}_{\text{F}}$ phenotypes can be seen as unfolding from intrinsic features of the zygotic nucleus. The gametocentric theory is committed to the idea that $\text{inherited}_{\text{F}}$ phenotypes can be seen as unfolding from intrinsic features of the zygote. In Weismann's version, $\text{inherited}_{\text{F}}$ phenotypes were seen as resulting from an unfolding of nuclear components called 'ids' and 'determinants'. In the preformationist version of the 17th century, $\text{inherited}_{\text{F}}$ phenotypes were thought to be 'given' already formed by parents to offspring at the moment of conception and the unfolding of phenotypes was nothing but the process of growth in size. And so on.

The metaphor of development is an attractive metaphor because the unfolding theory is an attractive theory. This theory is attractive because it is simple in that it explains development without mentioning factors external to the organism, i.e. it does not appeal to (conceptional or post-conceptional) relational features. And it is an attractive theory also because it fits very well with the (possibly universal) pre-theoretic intuition according to which living

organisms are relatively closed systems: what happens to living organisms is intuitively seen as due in most cases to forces *internal* to the organisms; and this applies especially to what happens to living organisms during development. But despite its appeal, the unfolding theory does not seem compatible with what we have come to learn about the development of phenotypes.

Explanatory spread in the theory of development

Saying that the occurrence of x is explanatorily sufficient for the occurrence of y is not equivalent to saying that x is causally sufficient for y. Explanatory sufficiency does not entail causal sufficiency. Or, to put it the other way around, the fact that something is causally required does not mean that it is also explanatorily required.[6] For any phenomenon, there are very many causal factors and conditions that must be in place in order for the phenomenon to occur. But, in order to explain the phenomenon's occurrence, we do not need to mention all these factors and conditions. Otherwise, in most cases, explanation would be virtually impossible. Only a proper subset of the factors and conditions required for the phenomenon to occur need to be mentioned in the explanation of the phenomenon's occurrence. The other factors and conditions can be taken as being part of the *explanatory background*, as holding *ceteris paribus*. What determines which factors involved in the occurrence of a phenomenon belong to the explanatory background and which belong to the explanatory foreground? This is a difficult question and I have no general answer to offer. But in order to clarify the DNA-centric theory and the conception/donation theory and to show why they are problematic, we need to make some sense of this distinction at least in this context.

As we saw, the DNA-centric theory of inheritance$_F$ entails that DNA is explanatorily sufficient for the development of those phenotypes that are subject to the like-begets-like phenomenon. That is, it entails that DNA is explanatorily sufficient for the development of reliably reoccurring (inherited$_F$) phenotypes.[7] But this does not mean that the DNA-centric theory entails that DNA is *causally* sufficient for the development of reliably reoccurring phenotypes. If the DNA-centric theory entailed this, it would then be very easy to show that this theory is wrong. DNA is not causally sufficient for the development of *any* phenotype. DNA molecules in a vacuum in outer space do not produce anything. Nongenetic factors are causally necessary for DNA to give rise to phenotypes.

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[6]The assumption here is that, if x is explanatorily necessary for y, there is no sufficient explanation for x that does not mention y.

[7]It is worth noting that the DNA-centric theory of inheritance$_F$ is not committed to the explanatory sufficiency of DNA for the development of phenotypes that are not reliably reoccurring (i.e. that are not inherited$_F$).

Let P be a phenotype. Despite the fact that DNA is not causally sufficient for the development of P, it could still be that all the nongenetic factors required in order to cause the development of P can be safely taken to be part of the explanatory background. That is, it could still be that none of these nongenetic factors needs to be explicitly mentioned in a satisfactory explanation of the development of P. In this case, DNA would be explanatorily sufficient for the development of P (cf. van der Weele 1999). So, from the fact that the DNA-centric theory entails that DNA is explanatorily sufficient for the development of reliably reoccurring (inherited_F) phenotypes we can infer that the DNA-centric theory entails that none of the nongenetic factors involved in the development of reliably reoccurring (inherited_F) phenotypes needs to be mentioned in a satisfactory (sufficient) explanation of the development of these phenotypes.

The view that DNA is explanatorily sufficient for the development of inherited_F phenotypes is the received view among developmental and molecular biologists. Development is often described as a sequence of genetic activations and inhibitions: the G1 genes produce chemicals that activate the G2 genes and inhibit the G2* genes, the G2 genes produce chemicals that activate the G3 genes and inhibit the G3* genes, the G3 genes produce chemicals that activate the G4 genes and inhibit the G4* genes, and so on. Watson and Dewey (1987: 748) ask: 'How [...] can we understand development at the molecular level?' And they answer: '[The] gene products responsible for development can be arranged in a hierarchy, with some genes controlling the expression of other genes'. The newest version of the unfolding theory is one according to which development is a cascade of gene-induced gene expressions (e.g. Raff and Kaufmann 1991; Wolpert 1991; Olson 2004). In order for these cascades of gene expressions to occur some nongenetic factors must also be present, but these factors need not be mentioned in molecular explanations of developmental processes.

Can the strategy of taking nongenetic factors to be background in the explanation of the development of inherited_F phenotypes be justified? One standard way to justify this strategy consists in saying that DNA provides the 'information' necessary to build inherited_F phenotypes while nongenetic factors only provide the materials needed to build these phenotypes. We are faced with a new metaphor: *the metaphor of information*. On one of the most popular versions of this metaphor, inherited_F phenotypes are 'cakes', genomes provide 'recipes' for these cakes, and the environment provides 'ingredients' (e.g. Dawkins 1999, 1986, 1996; see also Williams 1992).[8]

Developmental systems theorists have launched a strong attack against the notion of genetic information (Oyama 2000a, b; Gray 1992, 2001; Griffiths and

[8]Another version of the metaphor of information is the one according to which the genome is the program which determines which inherited_F phenotypes are generated and development is the unfolding (the execution) of this program (e.g. Jacob and Monod 1961; Bonner 1965; Wolpert and Lewis 1975; for a discussion see Fox Keller 2000, 2002).

Gray 1994, 1997, 2001; Griffiths 2001, forthcoming). They argue that the distinction between genetic informational causes and nongenetic noninformational causes (in development) is unprincipled, empirically unjustified, and based on false metaphysical preconceptions. They also try to use their arguments against the notion of genetic information as arguments against the DNA-centric theory of inheritance. Criticisms against the notion of genetic information have come also from authors that do not belong to the DST tradition (Godfrey Smith 1999; 2000; Fox Keller 2002). Against these criticisms, some have tried to elaborate at least a partial defence of the notion of genetic information (Sterelny et al. 1996; Wheeler and Clark 1999; Maynard Smith 2000; Sterelny 2000 see also Kitcher 2001).

Luckily, we can avoid going into this complex debate. The reason is that even if we grant that genetic causes of development are informational causes and that no other causes of development are informational (at least for the cases of inherited$_F$ phenotypes), it still does not follow that genetic causes of development are explanatorily sufficient and that nongenetic causes can be taken as explanatory background. If we want to explain the features of a cake, reference to the recipe used in order to make it will not usually be enough. A good explanation will have to say which ingredients have been used and their quality; it will have to say which cooking and baking devices have been used and perhaps how they have been used; and it will have to say who the cook or baker was and what competences he or she has. A cake made with poor quality ingredients is usually a bad cake, as it is a cake made by someone who cannot deal with the cooking devices or the ingredients properly, independently of what the recipe is. Recipes are not sufficient to explain the features of cakes; so, why should genetic recipes be sufficient to explain phenotypic cakes? The metaphor of genetic information cannot by itself be enough to justify the view that all nongenetic developmental factors are just explanatory background (contrary, for example, to what claimed by Wheeler and Clark 1999). And this, by the way, also shows that the DST strategy of attacking the DNA-centric theory of inheritance by attacking the notion of genetic information cannot be successful.

In this context, it is interesting to note that the metaphor of phenotypes as cakes appears for the first time not in Dawkins but in Bateson (1976, 2001; Bateson and Martin 1999) and that Bateson – differently from Dawkins – uses this metaphor to argue that phenotypes are the result of the complex interactions between genetic and nongenetic ingredients, that genes are not explanatorily privileged, and the it is impossible to quantify the causal contribution of genetic and nongenetic factors.

What other justification could there be for the view that nongenetic factors are not explanatorily necessary? Another attempt to answer this question appeals to the idea that among all developmental factors only genetic factors are under natural selection and thereby only the genome can be seen as having been designed (or programmed) to produce certain phenotypes. I have argued at length against the view that only genetic factors are the ultimate target of

natural selection in Mameli (2004).[9] But, even if we grant that only genetic factors are the ultimate target of selection, it does not follow that nongenetic factors should not be explicitly mentioned in developmental explanations. Development may be the result of the causal interaction of genetic selected factors and nongenetic nonselected factors, but this by itself is no reason to think that genetic selected factors deserve to be explicitly mentioned in developmental explanations and nongenetic nonselected factors do not.

For many biologists, the rationale for the view that, at least in the case of reliably reoccurring (inherited$_F$) phenotypes, nongenetic factors can be taken as explanatory background has probably to do with the notion of developmental *specificity*. After having conceded that there is a sense in which both genetic and nongenetic factors can be seen as causally involved in the developmental process, Gilbert (2003a: 349) adds: 'However, the specificity of the reaction (that it is a jaw that forms and not an arm; that it is a salamander jaw that forms and not a frog jaw) has to come from somewhere, and that is often a property of the genome.' Nongenetic factors are, in most cases, only 'nonspecific growth factors' or 'structural support'. There are developmental causal factors that provide specificity and developmental causal factors that do not; usually, genetic factors belong to the first class of factors and nongenetic factors to the second (cf. Raff and Kaufmann 1991).[10]

I believe that intuitions about developmental specificity are the actual motivation behind biologists' use of informational talk in genetics. But this is something I do not have room to expand upon here. Instead, I will try to make sense of the notion of specificity. The idea seems to be that for the development of many phenotypes and in particular for the development of inherited$_F$ phenotypes, the environment is only a *general-purpose* source of matter, energy or other kind of 'support'. The environment just 'allows' the development of phenotypes to happen, and thereby it cannot explain any of the 'specifics' of phenotypes. Genes are the only source of specificity. It is because of genes and not because of the general-purpose environment that development results, say, in a limb rather than a head, or in a limb with shape x rather than shape y. Since it is obvious that to make a phenotype one needs matter, energy and other forms of environmental 'support', it follows that it is not necessary to mention nongenetic factors in the explanation of the development of phenotypes that reliably reoccur. DNA is explanatorily sufficient.

Unfortunately for the supporters of this line of thought, it is not true that for all reliable reoccurring phenotypes the environment is not important in order to explain the structure of the phenotype. Consider, for example, musculo-

[9]See also Griffiths and Gray (1994, 2001); Sterelny et al. (1996); Sterelny (2001, 2004); Avital and Jablonka (2001). But the views and arguments presented in these papers are at least in part different from those presented in Mameli (2004).

[10]This is not what Gilbert thinks. After having made the distinction between specifying factors and nonspecifying ones, he argues that there are many cases in which the specificity comes from environmental factors; see also Gilbert (2001, 2003b, 2003c).

skeletal development in vertebrates. Microgravity studies show that gravitational force plays an important role in the development of the musculoskeletal features of vertebrates, especially in the case of large-size vertebrates like humans. Consider, in particular, the shape and structure of human legs. These phenotypic features are, on anyone's account, $\text{inherited}_{\text{F}}$ phenotypes and yet their normal development depends in crucial ways not only on the structure of the human genome but also on the amount of gravitational force that human beings experience on Earth while they grow up (cf. Thelen and Smith 1994). The value for gravitational force on the surface of our planet is around 9.8 m/s^2. If a human were to grow up on the surface of Jupiter – where the value for gravity is around 26.0 m/s^2 – or on the surface of Pluto – where the value for gravity is 0.6 m/s^2 – the shape and structure of his or her legs (and body in general) would be very different from the 'normal' (reliably reoccurring) one. This is one of the reasons why astronauts are not allowed to stay in outer space for too long and it is also one of the reasons why it would not be advisable for the children of astronauts to accompany their fathers and mothers during their missions. The environment is not just a general-purpose source of energy and matter; in this case, we have a nongenetic factor (gravity) that plays an important role in the developmental process and, thereby, it deserves to be explicitly mentioned in a satisfactory developmental explanation of why human legs have the shape and structure they have. There are genetic activations and molecular processes that are involved in the development of normal human legs and that do not occur in the absence of the normal gravitational value. DNA is not explanatorily sufficient.

Another interesting case is the role of ascorbic acid (vitamin C) in humans. Ascorbic acid is necessary for the correct synthesis of a kind of collagen that constitutes an important ingredient of normal skin, teeth, gums and capillaries. Lack of ascorbic acid causes skin sores, ulcers, tooth and gum problems, and burst capillaries (scurvy symptoms) owing to an abnormal type of collagen replacing the normal type in these tissues. That is, ascorbic acid is an important factor in the development and maintenance of normal skin, gums, teeth, and capillaries. DNA is not explanatorily sufficient for the normal development of these phenotypes. Humans cannot synthesize ascorbic acid. They have to acquire it from the environment by eating fruits (e.g. strawberries) and vegetable (e.g. broccoli). So, on anyone's account, ascorbic acid is a nongenetic factor for humans (cf. Nishikimi et al. 1994). Given its importance, it is a factor that deserves to be included in the explanatory foreground in developmental explanations of these phenotypes.

Yet another case worth mentioning is one concerning gut endosymbionts. All animals (both vertebrates and invertebrates) have microbes in their intestines and in almost all cases these microbes play important functions for their hosts. In many cases, their function is to help their animal hosts to digest some foods or substances that the animals would not otherwise be able to absorb. The digestive abilities of some animals (most herbivores) rely almost entirely on the activities of their intestinal microbial guests. In some cases, it has also

been shown that the microbes are partly responsible for the way the intestines develop: it has been shown that if the microbes are absent the intestines develop differently from the way they 'normally' do and certain kinds of 'normal' gene expressions do not occur (Bry et al. 1996; Umesaki et al. 1997; Hooper et al. 1998; Hooper and Gordon 2001; Hooper et al. 2001; Xu and Gordon 2003; Cherbuy et al. 2004). The microbes play an important role in the development of intestines with a given structure and digestive abilities. These symbionts cannot justifiably be ignored in developmental explanations.

Many other examples of the importance of specific portions of the biotic and abiotic environment for the development of specific phenotypes could be given. This holds for morphological as well as physiological as well as behavioural features. It can be argued that it holds for all phenotypes, or at least for very many of them. Many studies about phenotypic plasticity suggest that this is so.[11]

The majority of the existing studies are about environmentally induced phenotypic variation that occurs in nature. But the study of environmentally induced phenotypic variation that occurs outside the normal range of variation is also very important in this context. Many cases of natural phenotypic plasticity do not concern reliable reoccurring phenotypes – even though this is true to a much lesser extent than usually thought (Mameli 2004). The causal and explanatory importance of many environmental factors for developmental processes can only be unveiled by studying lab-generated environmental mutants. For example, the causal and explanatory importance of gravitational force for human leg development cannot be unveiled by studying the naturally occurring variation in leg shape and structure, for the simple reason that none of this variation is due to variation in the value of gravity. Contrary to current practices, nongenetic mutants (including those experimentally generated) should be granted the same kind of attention usually granted to genetic mutants.

The idea of the environment as a general-purpose resource for development is a relic of the old theory according to which all living organisms, in order to develop and survive, need some 'universal' elements like oxygen, nitrogen, hydrogen etc. – the so-called 'ingredients of life' – and nothing else. This idea is

[11]Schlichting (2002, 2003), Pigliucci (2001a, 2001b), West-Eberhard (2003), Herring (2003), Muller and Olsson (2003), Gilbert (2001, 2003a, b, c), van der Weele (1999); the essays in Gilbert and Bolker (2003); the essays in Oyama et al. (2001); the essays in Hall et al. (2003); Lewontin (1993, 2000); for behavioural phenotypes in particular see Bateson (1976, 1983, 2001), Bateson and Martin (1999), Gottlieb (1992, 1997, 2003), Avital and Jablonka (2001), Moore (2003), the essays in Bateson (1991), Kendrick et al. (1998), Immelmann (1975), Marinier and Alexander (1995), see also Mameli (2001, 2002); concerning the metabolic and behavioural importance of symbionts see Douglas (1994), Paracer and Ahmadjian (2000); the essays in Margulis and Fester (1991), Margulis (1998), Margulis and Sagan (2002), Wakeford (2001), Moran and Telang (1998), Rothstein and Robson (1998) and Smith and Read (1996); microgravity studies show that gravitational force is an important factor in very many developmental and biological processes in animals, plants and unicellular organisms, see Wassersug (1999), Hammond et al. (2000); the essays in Bonting (1991, 1992, 1993, 1994, 1996, 1997, 1999); the essays in Marthy 2003); the essays in Cogoli (2002).

incompatible with what we now know about developmental and biological processes in general. It is true that the environment provides sources of energy that living organisms exploit for their development and proper functioning; but the sources of energy used by different organisms are different. And it is true that the environment provides materials that organisms use to develop or maintain phenotypes and to replace malfunctioning parts; but the materials needed for different phenotypes are different. Moreover, environmental factors actively contribute to the sequence of gene activations and inhibitions that developmental and molecular biologists usually focus on. The cascades of gene expressions are highly sensitive to environmental factors such as temperature, gravity, the presence of environmentally derived chemicals, etc. The specificity of developmental processes is due to genetic as well as nongenetic factors and this means that, in many cases, nongenetic factors need to be mentioned explicitly in developmental explanations.

In conclusion, the distinction between explanatory sufficiency and causal sufficiency is of no help for arguing that DNA is explanatory sufficient for the development of phenotypes. If DNA is not explanatorily sufficient for development, then the present-day version of the unfolding theory of development needs to be abandoned. The examples I have provided indicate that all unfolding theories of development need to be abandoned, not just its DNA version. The intrinsic conceptional features of an organism – both genetic and nongenetic – are not sufficient to explain the development of the organism. It is certainly true that some of the nongenetic factors that need to be mentioned explicitly in developmental explanations reside inside the organism at the moment of conception. This is for example the case of all the incredibly important maternally produced nongenetic materials that can be found in the egg and then in the zygote at the moment of conception (e.g. Lacey 1998; Mousseau and Fox 1998; Hall 1999; King 2002). But such factors are only a small portion of the explanatorily important nongenetic factors. Many of these factors reside outside the organism and their impact on development does not necessarily start at conception, i.e. there are lots of developmentally important relational nongenetic features that organisms have.

The simplicity and intuitive appeal of the unfolding theory of development clashes with what we have discovered about developmental processes. We used to think that the relation between genotype and phenotype and the relation between zygote and adult form were relatively simple and relatively impermeable to external influences. But the scientific study of these relations has led us to find out that this is not so (cf. Bateson and Martin 1999; Fox Keller 2000).

Explanatory spread in the theory of inheritance

In the previous section, I argued that genetic features and other intrinsic conceptional features are not explanatorily sufficient for the development of

phenotypes, not even for the development of reliably reoccurring (inherited$_F$) phenotypes. In this section I explore the consequences of this claim for the DNA-centric theory and, more generally, for the conception/donation theory.

I start by introducing the ideas of causal and explanatory spread. These notions were first introduced by Wheeler and Clark (1999); here, I redefine them for my own purposes. *Causal spread* occurs when we discover some new factor causally involved in the occurrence of a phenomenon. *Explanatory spread* occurs when we realize that some factor that was not considered to be necessary in the explanation of a phenomenon is instead explanatorily necessary for that phenomenon. Or, to put it differently, explanatory spread occurs when we realize that some factor that was not taken to be part of a sufficient explanation of a phenomenon needs to be included in such explanation. Since the fact that something is causally required does not entail that it is also explanatorily required, causal spread does not necessarily lead to explanatory spread. But in cases where the newly discovered causal factor is deemed to be an important one, causal spread is likely to generate the inclusion of the newly discovered factor in any sufficient explanation of phenomenon to which this factor causally contributes. That is, in these cases, causal spread leads to explanatory spread.

Developmental studies have generated a substantial amount of causal spread in our understanding of development: many nongenetic developmental factors have been discovered that play a causal role in gene expression and development in general. Many of these nongenetic factors have been found to play an *important* causal role in determining the structure of phenotypes and thereby these new factors should become part of the explanatory foreground in developmental explanations. Causal spread in the theory of development should lead to explanatory spread in the theory of development. Should explanatory spread in the theory of development lead also to explanatory spread in the theory of inheritance? My answer to this question is: Yes.

Suppose you want to explain why your favourite cake, the one you buy at a local bakery every Saturday morning, always has the same great taste, week after week. In this explanation, you may well have to mention that the recipe and the cooking devices (including the oven) being used are the same, that the ingredients are of the same kind (the eggs are always fresh, the flour being used is of a special brand, etc.), and that it is always the same bunch of very skilled people who bake the cake, week after week. And if this is so, you also have to say how it is that all these factors remain constant week after week. For example, you may have to appeal to the policy of the bakery owner or to the habits of the people who actually bake the cake. If recipe, ingredients, cooking devices and cooking skills are all necessary factors for explaining the taste of the cake, then an explanation of why the cake tastes the same every week has to say that all these important factors remain constant week after week and it has to say how this happens.

Something analogous applies to reliably reoccurring (inherited$_F$) phenotypes. Let g_1 and g_2 be genetic factors, e_1 and e_2 environmental (nongenetic)

factors, and P a reliably reoccurring phenotype. If g_1, g_2, e_1, and e_2 are all necessary for explaining the development of phenotype P, then the reliable reoccurrence of g_1, g_2, e_1, and e_2 is necessary to explain the reliable reoccurrence of P. And, if this is so, an explanation of how it is the case that g_1, g_2, e_1, and e_2 reliably reoccur is also necessary. This means that DNA-copying and DNA-transmission are not explanatorily sufficient for the reliable reoccurrence (inheritance_F) of P. DNA-copying and DNA-transmission may be sufficient to explain the reliable reoccurrence of g_1 and g_2 but they do not explain the reliable reoccurrence nongenetic factors. Mechanisms other than DNA-copying and DNA-transmission have to be mentioned in an explanation of the reliable reoccurrence of e_1, and e_2 and thereby in an explanation of the reliable reoccurrence of P.

Let us go back to the examples presented in the previous section. If we want to explain why the shape and structure of the legs of human offspring reliably have the same shape and structure as the legs of human parents, we have to mention not only the reliable reoccurrence of the genes involved in normal human leg development, but also the fact that humans experience roughly the same amount of gravitational force from one generation to the next. And this means that, when we explain the reliable reoccurrence (inheritance_F) of legs with a certain structure and shape in human lineages, we have to mention not only DNA-copying and DNA-transmission, but also those processes that explain why human beings experience the same amount of gravitational force generation after generation.

In the same way, if we want to explain why 'normal' skin, gums, teeth and capillaries reliably reoccur in lineages of human beings, we have to mention not only the reliable reoccurrence of the genes involved in the development and maintenance of these phenotypes, but also the fact that foods containing ascorbic acid are reliably available to and consumed by 'normal' humans generation after generation. This means that, when we explain the reliable reoccurrence (inheritance_F) of normal skin, gums, teeth and capillaries in human lineages, beyond DNA-copying and DNA-transmission we also have to mention the processes that explain why foods containing ascorbic acid are reliably available to and consumed by humans beings belonging to these lineages.

Similarly, if we want to explain the reliable reoccurrence (inheritance_F) of normal intestines in animal lineages, we have to mention not only the reliable reoccurrence of certain genes but also the reliable availability of and interaction with certain kinds of microbial symbionts. DNA-copying and DNA-transmission are not explanatorily sufficient. The processes responsible for the reliable reoccurrence of interactions between animal hosts and microbial symbionts are explanatorily required too. These processes may have to do with parental behaviour in the animals (by means of which the parents infect the offspring with the right kinds of microbial symbionts), or with the behaviour of the microbes, or with the structure of the environment in which microbes and animals live. What is sure is that these processes consist in more than DNA-copying and DNA-transmission.

When the development of a phenotypic feature cannot be explained purely in terms of possession of certain genetic features, then the reliable reoccurrence (inheritance$_F$) of that phenotypic feature cannot be explained only by reference to DNA-copying and DNA-transmission, i.e. the processes that explain the reliable reoccurrence (inheritance$_F$) of genetic features. There also needs to be a reference to the processes that explain the reliable reoccurrence (inheritance$_F$) of the nongenetic features mentioned in the explanation of the development of the phenotype. The inheritance$_F$ of phenotypes is explained by both the inheritance$_F$ of genetic features (genetic factors) and the inheritance$_F$ of non-genetic features (nongenetic factors).[12] Even if we put cultural phenotypes on a side, the concept of inheritance$_F$ does not refer only to DNA-copying and DNA-transmission. And the concepts of inherited$_F$ and heritable$_F$ do not refer only to genetic features and to phenotypes whose development can be explained in purely genetic terms.

Explanatory spread in the theory of development generates explanatory spread in the theory of the inheritance of features. The DNA-centric theory of inheritance$_F$ is not a good theory of the like-begets-like phenomenon and thereby, despite its popularity, it should be abandoned. It is clear from what I have said that no version of the conception/donation theory can be a good theory of the like-begets-like phenomenon. Many of the nongenetic features that play an explanatorily important role in the development of reliably reoccurring phenotypes are not intrinsic conceptional features. Many of them are relational features and many are not conceptional features. Thereby, their reliable reoccurrence cannot be explained by the parent-to-offspring material transfer that occurs at conception. The conception/donation theory, despite its pedigree and in all its versions, should be abandoned too. Weismann's diagram should be replaced by the diagram in Figure 2.

I call this the *pluralistic theory of inheritance*$_F$. The horizontal arrows represent the processes that explain the reliable reoccurrence of developmental features. The horizontal arrows at the bottom represent DNA-copying and DNA-transmission, the processes that explain the reliable reoccurrence of genetic features. The horizontal arrows in the middle and at the top represent the mechanisms responsible for the reliable reoccurrence of nongenetic features. The difference between the arrows in the middle and those at the top is that those in the middle represent processes in which the parents are involved (e.g. the processes responsible for certain kinds of parent-to-offspring microbial transfer; cf. Paterson and Gray 1996; Sterelny 2001, 2004) while the arrows at the top represent processes in which the parents are not involved (e.g. the

[12]Some of the factors that affect the development of the phenotypes of an organism are genetic and some are nongenetic. To say that the development of an organism is affected by a given genetic factor is to say that the organism has a certain *genetic feature* and that this feature affects its development. Similarly, to say that the development of an organism is affected by a given non-genetic factor is to say that the organism has a certain *nongenetic feature* and that this feature affects its development.

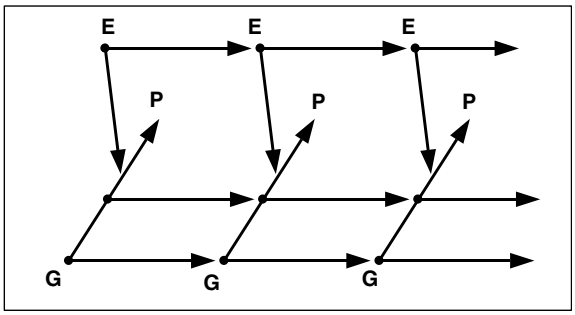

Figure 2. The pluralistic theory of the inheritance of features.

processes responsible for the stability of the value for gravitational force on planet Earth). This is only one of the many distinctions that can be made between different kinds of processes responsible for the reliable reoccurrence of nongenetic developmental features (Mameli 2004).

Another very important distinction is the one between processes of inheritance$_F$ that are involved in the reliable reoccurrence of *differences* between lineages and processes that are not. A proper understanding of the class of processes responsible for reliably reoccurring variation and of its internal subdivisions is necessary in order to understand the relation between inheritance, variation and natural selection. This is certainly a topic that needs exploration, but since it concerns the theory of inheritance$_V$ I will not talk about it here. (For the beginning of an exploration of these issues see Sterelny 2001, 2004; Mameli 2004).

It is interesting to note that even the claim that DNA-copying and DNA-transmission are explanatorily sufficient for the reliable reoccurrence (inheritance$_F$) of genetic features is not entirely correct. In sexual populations, the reliable reoccurrence of genetic features, especially those that involve the possession of more than one gene, needs to be explained not only in terms of DNA-copying and DNA-transmission, but also in terms of positive assortative mating, allelic frequencies and population structure in general. The processes of segregation and recombination break down gene complexes that are present in the parent and cause only some parts of these gene complexes to be inserted in the gametes. This means that these gene complexes are not likely to be transmitted intact from a parent to an offspring at conception (Dawkins 1999; Mameli 2004). But if the genes that constitute a particular gene complex G have a high frequency in the gene pool, then an organism with G is likely to have offspring with G. This is despite the fact that, due to segregation and recombination, the organism transmits to each offspring only some parts of G. And the reason for this is that, due to the high frequency of the G genes in the population, the offspring are likely to receive the missing parts of G through genetic transmission from the other parent. Similarly, if an organism with a given gene complex H is likely to mate with an organism with H, the organism

is likely to have offspring with H. Again, this is despite the fact that, due to segregation and recombination, the organism transmits to each offspring only some parts of H. Due to positive assortative mating, the offspring are likely to receive the missing bits of H through genetic transmission from the other parent.

Conclusions and further thoughts

In this paper, I have done three things:

(i) I have clarified the concepts that have to do with the inheritance of features.
(ii) I have explained some of the relations (both historical and conceptual) between the DNA-centric theory of the inheritance of features, the conception/donation theory, the metaphor of inheritance, the metaphor of development, the unfolding theory of development, the notion of developmental specificity, and the idea of explanatory sufficiency.
(iii) I have argued against the DNA-centric theory of the inheritance of features and – more generally – against the conception/donation theory and in favour of a pluralistic theory.

Criticisms against the DNA-centric theory have been formulated by other authors too.[13] The arguments presented by these authors and the conclusions they draw from their critique of the DNA-centric theory are (at least in part) different from the arguments and conclusions presented above (see also Mameli 2004). There is no room here to analyze these differences, but three of them deserve to be mentioned.

The first difference that I want to mention is the one between the claims I make in this paper and the views argued for by Sterelny (2001; 2004; Sterelny et al. 1996). Sterelny focuses only the causes of intergenerational similarity that can be involved in processes of cumulative natural selection. While I think that his project is extremely interesting and extremely important (Mameli 2002; 2004), I also think that a general theory of inheritance can and should abstract away from issues that have to do with cumulative selection and, more generally, with issues that have to do with variation and selection (whether cumulative or not). It is for this reason that in this paper I have not talked about the relation between inheritance and the theory of natural selection. I have focused on inheritance$_F$ and not on inheritance$_V$.

The second difference that I want to mention is the one between the views presented in this paper and the views argued for by developmental systems

[13] Oyama (2000a, 2000b), Gray (1992, 2001), Griffiths and Gray (1994, 1997, 2001), Griffiths (2001, forthcoming); Sterelny et al. (1996), Sterelny (2001, 2004), Jablonka and Lamb 1999), Avital and Jablonka (2001), Jablonka (2001), Laland et al. (1996a, 1999, 2000, 2001), Odling-Smee et al. (2003); Sapp (1987, 1994, 2003a, b), see also Gottlieb (2003), Immelmann (1975), Lacey (1998), Aufderheide (2002), Jablonka and Lamb (2002), Hurst (2002), Margulis and Sagan (2002).

theorists (Gray 1992; 2001; Griffiths and Gray 1994, 1997, 2001; Oyama 2000a, b; Griffiths 2001, forthcoming). I have already mentioned this difference above. It has to do with the fact that developmental system theorists believe that a critique of the notion of genetic information plays a fundamental role in arguing against the DNA-centric theory of inheritance. I think this is wrong. Even though I am not committed to the view that the notion of genetic information is theoretically useful, my arguments against the DNA-centric theory are compatible with such a view.

The third difference is also between my views and the views of developmental system theorists. I have argued that we should abandon the DNA-centric theory in favour of a *pluralistic* theory of the inheritance of features. The pluralism consists in being able to consider processes other than DNA-copying and DNA-transmission, i.e. processes that explain the reliable reoccurrence of nongenetic developmental features and thereby contribute to explaining the reliable reoccurrence of phenotypic features. Developmental systems theorists instead argue that we should abandon the DNA-centric theory in favour of a *holistic* theory of inheritance, according to which it is the whole life cycle that is involved in regenerating all the resources and in recreating all the interactions that are necessary to give rise to a new life cycle of the same kind.

Apart from the fact that the pluralistic theory seems preferable to the holistic theory on pragmatic grounds, I do not think there is any reason to adopt the holistic theory (see also Mameli 2004). This can be shown by appealing, once again, to the distinction between what is explanatorily required and what is causally required. It is true that very many (perhaps all) parts of a life cycle are causally necessary for the generation of another life cycle with similar features. But not all these parts need to be explicitly mentioned in explanations of the reliable reoccurrence (inheritance$_F$) of features. In order to explain the intergenerational reoccurrence of genetic factors, DNA-copying and DNA-transmission are – at least in many cases – explanatorily sufficient; there is no need to mention other parts of the parental life cycle. Similarly, in order to explain the intergenerational reoccurrence of symbiotic microbes, only some parts of the parental life cycle need to mentioned, i.e. those parts (if any) that cause the offspring to acquire the same microbes as their parents. And in order to explain the reliable reoccurrence of exposure to a certain amount of gravitational force, only the stability of the value of gravity needs to be mentioned; there is no need in this case to mention properties of developmental cycles.[14] Due to considerations of this kind, it seems to me that the pluralistic theory should be

[14]Except perhaps for the fact that we are talking about large-sized organisms whose development is significantly affected by gravitational force; see Lewontin's remarks about the different impact gravity has on vertebrates and invertebrates (Lewontin 1993, 2000). But there are also many ways in which gravity can affect what happens to small-sized organisms; see Hammond et al. (2000), Cogoli (2002).

preferred to the holistic one. But this is certainly a topic that needs further investigation.

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