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Determinism and Underdetermination in Genetics: Implications for Students' Engagement in Argumentation and Epistemic Practices

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Abstract In the last two decades science studies and science education research have shifted from an interest in products (of science or of learning), to an interest in processes and practices. The focus of this paper is on students' engagement in epistemic practices (Kelly in *Teaching scientific inquiry: Recommendations for research and implementation*. Sense Publishers, Rotterdam, pp 99–117, 2008), or on their practical epistemologies (Wickman in *Sci Educ* 88(3):325–344, 2004). In order to support these practices in genetics classrooms we need to take into account domain-specific features of the epistemology of genetics, in particular issues about determinism and underdetermination. I suggest that certain difficulties may be related to the specific nature of causality in genetics, and in particular to the correspondence between a given set of factors and a range of potential effects, rather than a single one. The paper seeks to bring together recent developments in the epistemology of biology and of genetics, on the one hand, with science education approaches about epistemic practices, on the other. The implications of these perspectives for current challenges in learning genetics are examined, focusing on students' engagement in epistemic practices, as argumentation, understood as using evidence to evaluate knowledge claims. Engaging in argumentation in genetics classrooms is intertwined with practices such as using genetics models to build explanations, or framing genetics issues in their social context. These challenges are illustrated with studies making part of our research program in the USC.

1 Introduction: How to Take into Account Epistemology in Science Learning?

In the last two decades, just as science studies have shifted from an interest in the products of science, its models and theories, to an interest in the processes and practices of science (Vicedo 2000), science education research has also shifted from an interest in the products and outcomes of learning, to an interest in the learning processes and in students' practices (Duschl and Grandy 2012; Kelly 2008). It is interesting to note that similar metaphors have

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been used to write about this shift: Marga Vicedo argues that "if we want to understand science, we must go beyond the clean work of analyzing reconstructed theories, and get our hands dirty by examining the practice of science" (Vicedo 2000, p. 215). Ann Brown (1992) described her studies of communities of learning as happening "in the blooming, buzzing confusion" of classrooms. In these decades a consensus has emerged in science education about the need for coherence between the production of scientific knowledge and its reconstruction in science classrooms, in other words, the need to take into account science studies, including history, philosophy and sociology of science (Duschl and Hamilton 1998; Kelly et al. 1993). Some lines of consensus, according to Duschl and Grandy (2008), have been a shift from science as experimentation to science as explanation/model building and revision, or the acknowledgement of the role of discourse in the construction of scientific knowledge. However, there is less agreement about which implications for science learning should be drawn from epistemology. Discussing in detail how science studies have shaped our understanding of science learning, or the competing views about it, is beyond the scope of this paper, which focuses on students' engagement in epistemic practices (Kelly 2008), as for instance knowledge evaluation, in the context of genetics. The argument of this paper is that, in order to achieve this engagement, we need to address reductionism and determinism in biology, and in particular in genetics, when teaching genetics.

In this introduction, first, three dimensions of the relationships between epistemology of science and science learning are discussed; second, recent developments in science studies, relevant to epistemic practices and argumentation in science learning, are summarized. The second section addresses domain-specific features of the epistemology of genetics, in particular issues related to determinism. The third section examines how the nature of causal mechanisms in genetics may influence students' practices and arguments.

1.1 Connections Between Science Learning and Epistemology of Science

Among the different debates on these connections there are three interrelated dimensions relevant for the purposes of this paper:

a. *Domain-general* and *domain-specific* features of epistemologies.
b. *Correct* versus *productive* students' epistemological positions.
c. *Complementary approaches* to the relationships between epistemology and science learning.

The first issue is the tension between studies focusing on features of knowledge construction and explanations that are explicitly or implicitly assumed as being common for all sciences, and studies emphasizing domain-specific characteristics and explanations of particular disciplines, as biology, or even genetics. Extreme forms of the first position would be reductionism, claiming that sciences as biology have not their own explanations, because these could be reduced to physics, or the notion of one single "scientific method". Serious objections have been raised against such reductions, Mayr (1997) points out the singularity of historical reconstruction in biology. Some authors have reconceptualised the debate in terms of complementarities: For Bechtel and Hamilton (2007) it is a question of integration rather than of unity; they discuss the implications of reduction for mechanistic explanations, as for instance molecular genetics, where knowledge of components is not enough to understand the whole. Longino (2000) advocates epistemological pluralism that recognizes the local character of epistemologies, and evaluates them by their ability to help a community to achieve understanding. Mitchell (2003) proposes an integrative pluralism:

the complexity of biological phenomena requires a plurality of models to account for them. It should be noted the distinction (Schaffner 1993) between ontological reductionism, reducing biological entities to molecules, or humans to their DNA, and methodological reductionism, a trend towards appealing to explanations at the lowest level possible. While the first would lead to determinism and there are many reasons to challenge it, some degree of methodological reductionism may be difficult to avoid in science classrooms. In science education Rudolph and Stewart (1998) discuss the nature of scientific practice in evolutionary biology and its implications for learning, Erduran (2007) addresses domain-specificity in chemical education about the periodic law, and Brigandt (2011) examines different pluralisms in the context of explanations in biology.

Alongside this trend towards pluralism, there is a coexistence of agreement in the field of studies about personal epistemologies, on what would constitute a sophisticated view about the nature of science (NOS) across the disciplines. Hofer and Pintrich (1997) identify four epistemological dimensions, beliefs about knowledge that need to be addressed: certainty (versus tentativeness), simplicity (versus complexity), source of knowledge (authority versus independence), and justification for knowing. But some criticisms have been raised against this consensus.

The second dimension deals with the characterization of students' sophisticated epistemologies, for instance viewing science as tentative, complex, and based on evidence. Elby and Hammer (2001) challenge this consensus view on two grounds: first they argue that some naïve beliefs (as certainty or naïve realism) may be productive in terms of supporting learning; second they contend that 'blanket' generalizations about the nature of knowledge (as considering tentative the idea of a flat earth) are neither correct nor productive. They suggest the need for attending to context, both disciplinary, as knowledge in some fields is more tentative than in others, and related to the issue under discussion. Their implications about research are, first the need for relying more on naturalistic methods and less on surveys that are inadequate for capturing these complexities, and second the suggestion to focus less on ranking beliefs, and more on "identifying productive epistemological resources that students can build upon (with their teachers' help) to become better learners." (Elby and Hammer 2001, p 565). Kelly et al. (1998) raise similar criticisms about the adequateness of surveys for investigating NOS beliefs.

The third issue addresses different perspectives about the relationships between science learning and epistemology, drawing from the work of Kelly et al. (2012). Kelly and colleagues identify three perspectives: (a) *disciplinary*, relying on philosophy of science in order to consider theory change or conceptual change in science learning; (b) *personal*, concerned with the ways students' personal epistemologies influence learning; and (c) *social practices* view, considering ways by which disciplinary practices, as for instance representing data, or engaging in special discourse, are enacted in learning contexts. They view these perspectives rather as overlapping and placing emphasis on certain dimensions of epistemology than as mutually exclusive. Each perspective defines particular research programs.

This paper is framed in the third perspective, as our focus is on students' actual epistemic practices, on what counts for them as scientific claims, evidence, justification or communication, rather than on their personal epistemologies (beliefs). As Kelly et al. (2012) point out, the knowledge examined here is not propositional, but enacted. These practices reveal students' *practical epistemologies* (Wickman 2004; Wickman and Östman 2002) or epistemologies used in specific practices. This perspective focuses on practical epistemologies as actions, rather than as beliefs, on students' and teachers' *actions* as

situated in an activity (Wickman 2011). In summary, epistemic practices are the actions that reveal students' underlying practical epistemologies.

This approach is embodied in Kelly's (2008) notion of *epistemic practices*, defined as "the specific ways members of a community propose, justify, evaluate, and legitimize knowledge claims within a disciplinary framework." (Kelly, p. 99). Kelly (2008) argues that participating in science involves learning the epistemic practices associated with producing, communicating and evaluating knowledge, consequently the goals of science education should include developing epistemic practices among learners. Argumentation is related to the evaluation of knowledge so we propose framing it in epistemic practices. Instances of this approach are argumentation analyses (Jiménez-Aleixandre et al. 2000; Kelly and Takao 2002), the examination about how students construct meanings for concepts and transform them into practical actions in the laboratory (Jiménez-Aleixandre and Reigosa 2006), or about how conceptual resources are activated in a learning situation in the laboratory (Hamza and Wickman 2008).

These three dimensions are interrelated: for instance, pluralist epistemologies would lend support both to Elby and Hammer's (2001) suggestion about the need to consider disciplinary contexts, and to Kelly's (2008) definition of epistemic practices as situated within a disciplinary framework. Elby and Hammer's (2001) proposal about the need for identifying productive epistemological resources is related to the analysis of students' epistemic practices, and to the identification of learning environments that better promote their development. Figure 1 is an attempt to capture these connections.

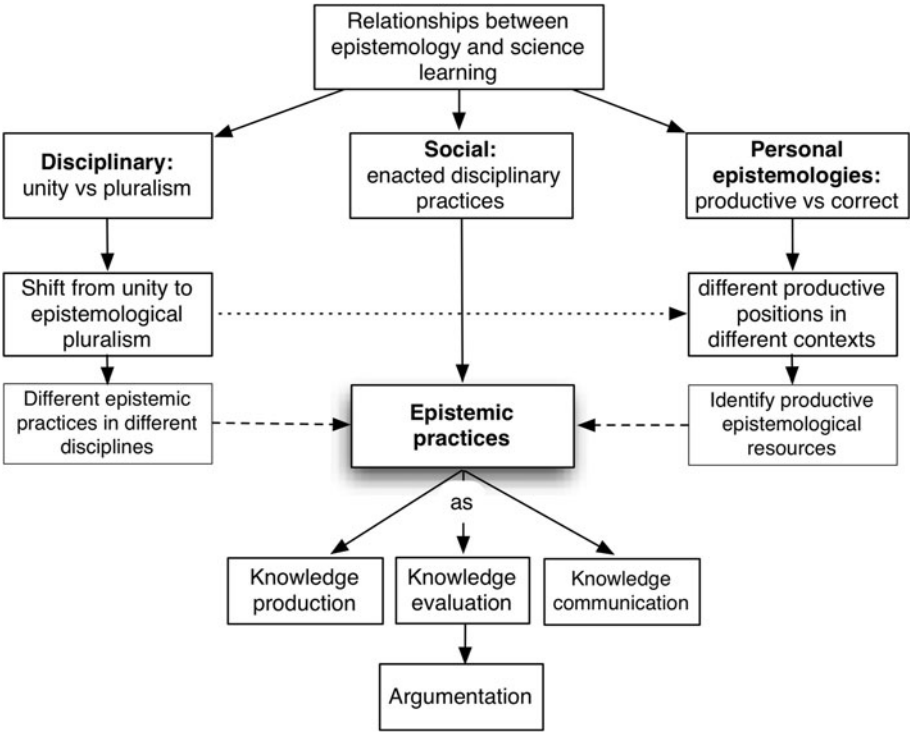

Fig. 1 Connections between epistemology and science learning

From this perspective, framing the paper's approach, next disciplinary perspectives that are relevant for epistemic practices and argumentation are reviewed.

1.2 Models and Modelling in Science Studies and in Science Education

Developments in science studies in the twentieth century have been summarized by Duschl and Grandy (2008) in three periods along a continuum where science has been conceived as an enterprise driven respectively by experiment, by theory, and by model. Their characterization of three emphases in the third perspective offers a useful frame for science education's approaches about: (a) the role of models and data construction and its relation to the role of theories; (b) the role of the scientific community, or the social character of scientific inquiry; and (c) the consideration of the cognitive scientific processes as distributed systems that include instruments. Each of these issues may influence current perspectives on science epistemic practices and argumentation.

Addressing the role of models, Ronald Giere (1988, 1992) sees science as a cognitive activity, and therefore proposes to use concepts and methods of cognitive science in order to study the development of scientific knowledge. Giere's approach to scientific reasoning rather as a process of decision making than as a one of inference has been used to frame studies of argumentation in science classrooms (e.g., Jiménez-Aleixandre et al. 2000). Giere emphasizes the role of choices among competing theories in the building of scientific knowledge. Choosing among competing explanations is one of the relevant contexts for engaging students in argumentation.

One influential view about philosophy of science in recent years is Helen Longino's (1990, 2002) perspective of science as social knowledge, establishing the relevance of social values and interactions to the construction of scientific knowledge. Longino (1990) undertook an analysis of scientific knowledge with the goal of reconciling the objectivity of science with its social and cultural construction. Recently she has explored the epistemological consequences of the recognition of the social character of scientific inquiry in connection to pluralism, or the acknowledgement of explanatory plurality (Longino 2002). For Longino (2008) knowledge itself is social, because what matters is what the scientific community comes to agree or disagree on. In my opinion the work of Jürgen Habermas (1981) is of relevance for the social character of science, although its focus is not on science, because of its emphasis on communicative action and shared norms. The implications of Habermas' and Longino's views for inquiry and science learning have been examined by Kelly (2008), who argues that they involve shifting from an individual to a social epistemic subject. Viewing scientific knowledge as socially constructed has influenced both the design of science classrooms as communities of learners, and the ways of studying classroom interactions, in particular the discursive ones, as argumentation. The work of Longino related to underdetermination in biology is discussed below.

The consideration of cognitive processes as distributed systems that include instruments draws from the work of Russian cultural-historical theorists as Vygotsky and Leont'ev (1978) conceived human action as mediated by tools and signs. The distributed cognitions approach has expanded some of the notions of this school of thought, as the activity systems (Cole and Engeström 1993) and the role of both physical and symbolic tools. Accounts of knowledge construction need to consider the role of instruments, as for instance the influence of technical developments in the microscope in the evolution of the concept of cell, and in Schwann's formulation of the cell theory (Bechtel 1984; Bechtel and Richardson 1993). This view has implications for the examination of students' epistemic practices enacted in social settings, as for instance laboratories.

Two relevant epistemic practices are argumentation (knowledge evaluation) and modelling (knowledge production). Svoboda and Passmore (2011) analyse modelling in biology in the context of its epistemic aims. Their work is informed by perspectives from philosophy of biology, in particular by Jay Odenbaugh. Their point is that different epistemic aims, such as producing an explanation or generating a prediction, lead to building different models. Duschl and Grandy (2012) propose that NOS learning occurs when students are engaged in cognitive, epistemic and social practices, a view that they term 'Version 2' about NOS teaching.

In summary, some recent trends in philosophy of science support a focus on studying students' practical epistemologies as situated actions—for instance engaging in model building or in model evaluation—in a particular community.

2 Epistemology of Genetics: Causal Explanations and Underdetermination

This section addresses some features of genetics epistemology, in particular those related to underdetermination. First, selected cases about how genetics knowledge was constructed are analyzed; second causality in genetics is discussed. A first concern about genetics epistemology, that is the construction of genetics knowledge, is to disentangle it from "genetic epistemology" (study of the origins of knowledge, established by Piaget) bearing a similar name, but addressing different issues.

2.1 The Troubled Construction of Genetics Knowledge

The history of the origin of genetics was a troubled one but some would think that, in the century elapsed since Mendel's paper was brought to attention, subsequent developments have been smooth. However some later findings went similarly unacknowledged, for instance Barbara McClintock's work on genetic regulation in the 40's, partly due to the dominance of the discourse based on the so-called central dogma of molecular biology, which ruled out any possibility of information flowing back from proteins and cells. "It is caused by genes" has been and still is an overarching explanation, both in scientific and in public discourse, sometimes extended outside its explanatory domain. Another instance may be the reception in 1982 of Prusiner's paper blaming proteinaceous particles (prions) for scrapie and "mad cow disease". How could proteins devoid of DNA propagate?, wondered a sceptical scientific community. Determinism and underdetermination have played and continue to play an important role in shaping both genetic knowledge and its public social understanding. My point is that they also influence how students learn genetics and how they engage in epistemic practices in genetics contexts.

It may be argued that few outstanding scientific works have been so roughly handled as Mendel's (1866). It is not accurate to say that his contemporaries did not read his paper, as it was quoted at least by eight authors (Brannigan 1979). The paper became the cornerstone of genetics, however controversy continued to plague it, were it about his author's epistemic approach, his truthfulness, or the circumstances of its rediscovery in 1900. Kampourakis (2010) points out that Mendel was not isolated, suggesting the need to place his work in the context of a community of researchers studying heredity, in a perspective of science as a social process.

A range of causes have been suggested for its lack of impact: (1) cognitive, related to understanding its meaning: for instance that Mendel's contemporaries failed to understand its statistical approach (Campbell 1980); (2) epistemological, related to what counted in his

time as good science: Zwart (2008) argues that his epistemological profile was out of tune with the scientific environment because he adhered to the principle of discontinuity, considering natural entities as combinations of discrete elements; (3) sociological, related to his author's position in the scientific community: Mendel did not belong to the scientific elite, so his paper was not acknowledged through informal communication channels (MacRoberts 1985). From these potential reasons, epistemological ones, what counted as good science, are the most relevant for the purposes of the paper. In my opinion, Brannigan's (1979) illuminating study dismantles these hypotheses, except the sociological one. Brannigan views Mendel's work as aligned with his contemporaries and seen, in 1866, as normal science. He offers an alternative explanation: that the significance of Mendel's paper changed over time: in 1900, read in the context of the dispute over continuous versus discontinuous variation, his discovery of segregation "constituted a relatively revolutionary achievement." (Brannigan 1979, p. 424). Kampourakis (2010) also points out to the different reception of the paper in 1866 and after 1900. Brannigan (1979) highlights the role of a priority dispute between Correns and de Vries, leading to the first one labelling segregation as "Mendel's law".

Mendel's paper became a classic, but controversy about it never ceased. First, the role of the scientists who allegedly "rediscovered" it has been disputed. Hugo de Vries lecture plates show that, before reading the *Versuche*, he used ratios as 77.5/22.5, or 80/20, that do not correspond to the Mendelian 75/25 or 3/1 pattern (Campbell 1980; Darden 1985). A plate that he presented as evidence of his independent discovery of the segregation laws was made later (Zevenhuizen 2000). De Vries only acknowledged Mendel's priority when criticized by Carl Correns (Brannigan 1979).

Second, the purpose and significance of Mendel's work has been disputed. The title of Olby's (1979) paper is revealing: 'Mendel no Mendelian?'. About his research question, Brannigan (1979) claims that he was studying hybridization rather than heredity. Should we expect a modern paper's structure in a work from 1866? In the introduction, although not labelled as "research objective", he states that no previous experiment had determined the "numerical" relations in the offspring of hybrids. This sentence counts as the paper research hypothesis: numerical relations do exist; there is a pattern. For Piquemal (1965) observing isolate traits means assuming that they are independently inherited; studying great samples means thinking in terms of probabilities. Therefore he assumes that Mendel framed his experiments in a theoretical hypothesis. Another issue is whether his work was more concerned with inheritance explanations or with speciation; he criticized the belief in that "the stability of the species is greatly disturbed or entirely upset by cultivation" (Mendel: 37), explaining plant variability because pertaining to hybrid series.

Third, Mendel has also been charged with falsification (Fisher 1936), a claim grounded on statistical analysis that originated a long controversy (Franklin et al. 2008). Fairbanks and Rytting (2001) conclude that Mendel did not fabricate his data and that he did articulate the laws of inheritance as much as was possible at the time.

From Mendel, we will move on to two cases that are examples of how discourses attributing to genes the final explanation of most biological phenomena influenced the development of genetics knowledge in the second half of the twentieth century.

From 1944 on Barbara McClintock studied genetic instability in the inheritance mechanisms of mosaic colour patterns in maize. She identified a mechanism of control of gene expression consisting of a two-unit controlling system, loci that she named Dissociator (Ds) and Activator (Ac), (McClintock 1950, 1953), concluding that: "Extragenic units carried in the chromosomes are responsible for altering genic expression […] The extragenic units represent systems in the nucleus that are responsible for *controlling the*

action of genes." (McClintock 1953, p. 598, emphasis added). Her work was regarded with scepticism when presented at the Cold Spring Harbor symposia, and she received only two reprint requests for her groundbreaking 1953 paper (Keller 1983); after that, she stopped publishing.

According to Keller, the gap between McClintock and her colleagues was due to two issues. First, the revolutionary implications of her findings, as they were contradictory with the predominant view: "if genetic elements were subject to a system of regulation and control […] what meaning was then left to the notion of the gene as a fixed, unchanging unit of heredity?" (Keller 1983, p. 144). Second, Keller argues that McClintock and her fellow geneticists did not share a common language (perhaps it can be called discourse), grounded on unarticulated premises and assumed practices, on a shared perception of what counts as evidence in a field. As Longino points out: "Background assumptions, then, include substantive and methodological hypotheses, which, from one point of view, form the framework within which inquiry is pursued […] These hypotheses are most often not articulated, but presumed" (Longino 2000, p. 273). It also needs to be noted that she, as other women scientists, experienced difficulties for progressing in her career, as lack of funding, promotion, or graduate students. Although Comfort (1999) claims to have identified the relevance of controlling elements in her work, which preceded Jacob and Monod's, and he downplays the gender discrimination that she faced, I suggest that a close reading of Keller (1983), shows her focus on (a) the challenges posed by the notion of genetic regulation to DNA 'central dogma', and (b) the different background assumptions of McClintock and other geneticists.

In summary, one of the most important factors explaining the delayed recognition of McClintock's work on genetic control is the dominance of the discourse based on genetic determinism, which denied the possibility of regulation. This was connected to a gap among her epistemological assumptions and those of her colleagues.

For many years it was assumed that spongiform encephalopathies, from which the mad cow disease BSE (bovine spongiform encephalopathy) is best known, were caused by 'slow viruses'. In the 60's Griffith proposed that the agent could be a protein, meeting criticism, for instance from Crick, because it contradicted the so-called 'central dogma of molecular biology' stating an univocal flow of information, DNA to RNA to protein, which precluded protein–protein transmission. Stanley Prusiner (1982) showed that scrapie, another disease of the same type, was caused by a proteinaceous infectious particle (that he called 'prion'), different from viruses or other agents containing nucleic acids. Prions propagate, not through nucleic acids, but through transmission of a misfolded protein state to other proteins. As Prusiner states in his autobiography in the occasion of the Nobel Prize in 1997, the publication of the paper set off a firestorm. The notion of prions was received with incredulity; awarding of the Nobel Prize to Prusiner was debated, and there are still some researchers (e.g., Manuelidis 2007) who claim that slow viruses are the cause of these degenerative diseases.

This brief analysis of historical cases helps us to uncover the processes involved in how scientific ideas get into society, or in how research findings are transformed into scientific knowledge. Three aspects of relevance for students' involvement in the scientific practices of modelling and argumentation in the context of genetics learning (and in other science fields) may be:

1. *What counts as acceptable science*, theoretical frame, research questions or evidence, is disputed and *changes over time*. The process of *communication*, a scientific practice sometimes overlooked, plays a crucial role in the legitimization of scientific

knowledge. The analysis of students' practical epistemologies attends to what counts as science for them, and how communication among them shapes meanings.

2. *Identifying patterns* in data poses challenges to scientists, as evidenced by de Vries' difficulties and by the delayed acknowledgement of McClintock's work, and it is related to framing data in theories. It is not surprising that this operation, involved in the use of evidence and argumentation, would also be difficult for students. Two implications may be: first the need to articulate relevant theoretical knowledge and use of evidence; two the relevance of teacher's scaffolding.
3. *Probabilism versus determinism*: in Mendelian genetics, patterns are expressed in *probabilities*, however the orientation of school textbooks is rather determinist (Jiménez-Aleixandre 1994). This does not help students to acknowledge the role of chance and to think about genotypes and phenotypes in terms of probabilities.

These are examples about how reductionism and determinist discourses dominated the scientific community. It is not only a question of including chance in the explanations, but of acknowledging the complexity of the mechanisms. A similar dominance can be found in other social settings as the media or genetics lessons. Next causal mechanisms in genetics and how they have been subjected to determinist interpretations are discussed.

2.2 Determinism and Underdetermination

Studies about philosophy and epistemology of biology point out the inadequacy of reductionist and determinist accounts in genetics. In this section this issue is discussed in relation to the nature of causality in genetics. It needs to be noted that the current view of the model of gene expression, accounting for the relationships between genotype (the genetic constitution of an individual, characterized at a molecular level) and phenotype (the expressed characteristics) views phenotype as resulting from gene-environment interactions. Human height is a classical example: a person may develop or not her full potential height, depending on diet, health conditions and physical exercise.

Epistemological studies examine what counts as data, evidence or appropriate methods to produce knowledge. Focusing on biology, a collection of essays (Creath and Maienschein 2000) brings together a range of epistemological issues, among them determinism. Magnus (2000) discusses competing epistemologies about speciation between Jordan and de Vries, representing the naturalist and experimentalist approaches. He traces back genetics reductionism to the first years of the twentieth century: "Ultimately, all biological phenomena should be explained in terms of genetics" (Magnus, p. 95). As he notes, although Jordan and the naturalists won the theoretical battle about speciation, they lost the epistemological one about what counts as good science.

Discussing the challenges posed by genetics to reductive accounts, Bechtel and Hamilton (2007) point out that several molecular mechanisms could produce the same phenotypic trait (multiple realizability), while the same molecular mechanism can produce different phenotypic effects if environmental conditions vary. An instance is the genetic code: some amino acids are encoded by only one codon, as methionine (by AUG), while others, as leucine, may be encoded by six different codons, what is known as *redundancy*. On the other hand, AUG, besides coding for methionine, serves also as the translation initiation site in mRNA. Even the path DNA to RNA to proteins is far from simple. However, as Bechtel and Hamilton (2007) note, the so-called central dogma entailed an explicitly reductionist gene-based approach, accounting not only for phenotypes, but also for human behaviour, altruism or belief in God.

Keller (2000), examining the limitations of the notion of genes as causes of development, notes the persistence of the discourse of 'gene action' in the view that "the development of a trait or function has been *explained* when the gene or genes 'for' that trait or function have been identified" (Keller, p. 248, author's emphasis). Keller suggests an alternative focus on developmental stability, which would lead to different research questions. Instead of asking which phenotypic failure is caused by mutation in one gene, she suggests examining the reliability of the developmental process, and the role of redundancy in guaranteeing it. This stands in opposition to the genetic paradigm, which considers redundancy as a problem. As Keller notes, fidelity in the transmission of information requires redundancy. She points out how over-emphasis on the explanatory power of sequence information may have been employed in order to secure research funding. In a recent book Keller (2010) takes further the focus on development, challenging the notion of an opposition between nature and nurture. Some of her challenging claims are that the very notion of a gene as an autonomous element is a fiction, or that "to think of the development of traits as a product of causal elements interacting with one another" (Keller, p. 6) is a mistake, because development depends on the complex orchestration of multiple courses of action, involving interactions among many kinds of elements.

A prominent critic of genetic determinism is the evolutionary biologist Richard Lewontin (1991). He takes issue with the view of genes as the ultimate mechanism of causation, arguing that biological phenomena are the result of interactions among genes, chance and environment. He considers biological determinism as a form of ideology, the view that humans differ in fundamental abilities because of biologically inherited innate differences. Lewontin argues that biological ideology is characterized by an impoverished notion of causation that confuses *agents* with *causes*. For instance, the agent for tuberculosis is the tubercle bacillus (TB), but although a third of the world's population might be infected with it, only a 10 % of latent infections develop to active disease. As Lewontin notes, in the nineteenth and early twentieth centuries tuberculosis was endemic, affecting particularly the poor. Its dramatic decrease, which happened before antibiotics, is attributed to improvements in nutrition and, to a lesser extent, in health conditions. He also exposes the ideological and political agenda associated to determinism and racism (Lewontin et al. 1984).

Lewontin (2000) claims that evolutionary genetics has a particular epistemological "texture" that is not analogous to physics. He argues that there are a large number of biological mechanisms, each of which may enter in different ways and times into the trajectories of different populations. This diversity is due to differences in the organisms, the environment and the stochastic nature of the operations, their non-deterministic behaviour, with intervention of random elements. Therefore, it would be difficult to draw universally applicable quantitative accounts of processes such as mutation or selection. As the editors (Creath and Maienschein 2000) point out in their introduction, the philosophical term for these circumstances is *underdetermination*, even if Lewontin does not use it. He does point out that population geneticists have been, like other scientists, educated to believe in a naive univocal model of science, in the assumption that quantitative evaluation of all relevant causal variables is the mark of good scientific explanations. They would then be dissatisfied with statements involving qualifiers as "*virtually all* populations show a lot of enzyme polymorphism" (Lewontin, p. 194, author's italics), that he expresses in the general form of "x can happen" or "y sometimes happen". However, he concludes that for evolutionary phenomena, "with so many weakly determining and interacting causal pathways […] that is the best that can be done." (Lewontin, p. 194).

For Longino (2000) the nature-nurture debate begins with different research questions: behavioural genetics asks which proportion of the variation in a trait is owing to variation in genes and which one to variation in environment, while the question for the environmentalists is what social or environmental circumstances nurture a disposition for and elicit the expression of a given trait. From the implications of underdetermination that she discusses, one that may be relevant for argumentation in classrooms is her suggestion that justification should be treated not just as a matter of relations between statements or beliefs of an individual, "but as a matter of relations within and between communities of inquirers." (Longino 2000, p. 274). In this socializing move, establishing what counts as data, evidence or reasoning becomes a matter of critical social interactions, helping to make visible implicit assumptions.

To these epistemology studies criticizing determinism, we may add Venter et al. (2001) conclusion in their paper about the human genome sequence:

> There are two fallacies to be avoided: determinism, the idea that all characteristics of a person are 'hard-wired' by the genome; and reductionism, the view that with complete knowledge of the human genome sequence, it is only a matter of time before our understanding of gene functions and interactions will provide a complete causal description of human variability (Venter et al. 2001 p. 1348).

In summary, causality in genetics, as viewed by contemporary epistemology, is far from simple and univocal. Instead of considering genes as causes (let alone as the sole causes) for diseases as cancer, or for complex performances as intelligence, it would be more adequate to think of causality in genetics in terms of sets of interacting causal factors. Would we say for instance that genes are the cause for the sex of a newborn? Human sex is dependent from which sex chromosomes, XX or XY, an individual possess. However, chance plays a major role in deciding which type of spermatozoid (X or Y) will reach the ovule, and there are other factors as the time of intercourse in relation with the ovulation cycle. A complex balance of hormones, during intra-uterus and external development, also influences a baby's sex. As an example, Fig. 2 summarizes some of the factors accounting for gene expression, in terms of relationships among, on the one hand chance, genes, regulation and environment and on the other a range of potential phenotypes, rather than a single one.

3 Students' Epistemic Practices and Epistemological Resources in Genetics

Epistemology and philosophy of science studies agree on discarding reductionism and genetic determinism, on criticizing simplified accounts attributing to genes all the responsibility for human traits and performances. Nevertheless, these accounts tend to prevail in public communication, in school science and even in the scientific community. For instance, in spite of the explicit acknowledgement about its limitations quoted above, genome sequencing is represented in the media as the "final explanation" for human characteristics, and publicized, with commercial purposes, for predicting risk factors for diseases such as cancer. We might ask about the reasons for this discordance between epistemological and public discourses (including school discourses) concerning genetics causation. Simplistic accounts, featuring single causes and straightforward relationships one cause—one effect, are more intuitive and easiest to transform into popularized summaries or journal reports, in comparison with set of factors related to a range of potential effects –as represented in Fig. 2—or, as Longino (2000) says, an immensely complex web of interactions. In this section the implications of determinism and underdetermination for

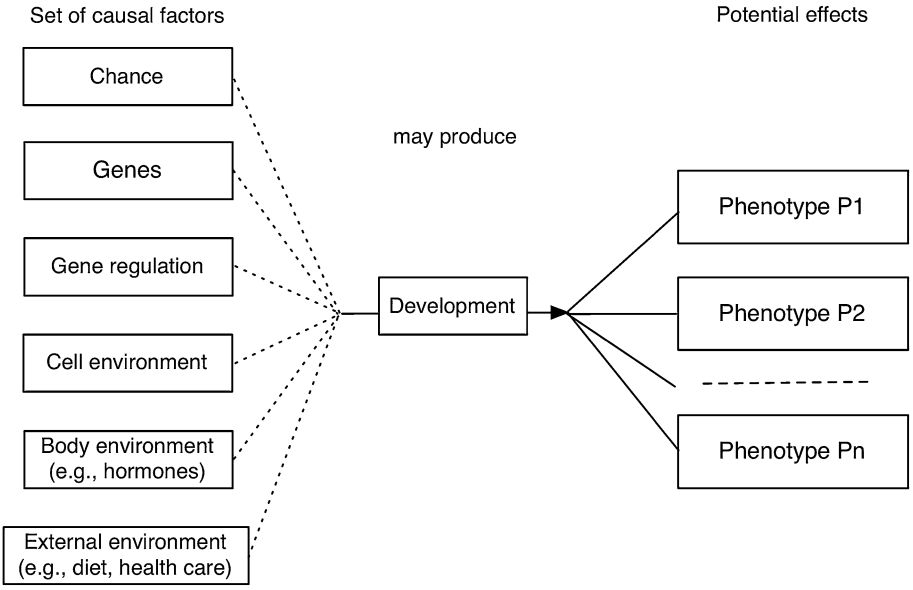

Fig. 2 Causality in gene expression: Interacting set of factors resulting in a range of potential phenotypes

student's engagement in epistemic practices in genetics are examined. Three issues are considered: first, students' epistemological resources relevant to genetics, as probabilistic thinking, acknowledgement of uncertainty and commitment to consistency of explanations; second, argumentation and the evaluation of evidence about genetics; and third, causality in the construction and use of the model of gene expression. These challenges are illustrated with studies making part of our research program; project RODA (ReasOning, Discourse, Argumentation) in the University of Santiago de Compostela.

3.1 Epistemological Resources

I agree with Elby and Hammer (2001) in viewing sophisticated epistemologies as a matter of developing and using epistemological resources, often implicit, in a given context. In genetics learning, I suggest that there are at least three relevant resources: probabilistic thinking, acknowledgement of uncertainty and commitment to consistency of explanations. Of course they may also be relevant for other science fields.

Probabilistic thinking is necessary in order to understand genetics, from Mendelian models and genetics problems to the model of gene expression. It has relevance in order to make sense of genotype and phenotype patterns in offspring, and to the understanding of chance in mechanisms such as meiosis, formation of gametes and fecundation, as well as in understanding evolutionary explanations (Kampourakis and Zogza 2008). Piaget and Inhelder (1951) studied its development, concluding that the fundamental notions of probabilistic thinking are only constructed at the stage of formal reasoning, although studies in mathematics education have challenged this claim, developing strategies for teaching it to younger pupils. In science education studies about genetics learning have discussed the relevance of probabilistic thinking and students' difficulties (e.g., Banet and Ayuso 2003). These difficulties suggest the need for addressing it in genetics teaching. However, an analysis of eight Spanish biology textbooks for 9th grade (Jiménez-

Aleixandre 1994) showed a prevalence of deterministic orientations, both in the presentation of Mendel's laws, with sentences as "half of the male sons will suffer from haemophilia" (instead of "there is a probability of half…"), and in problems, which presented exact proportions "216 black flies and 72 white flies". Only one textbook had a probabilistic orientation.

I suggest that if this resource is underdeveloped or not developed, it would be very difficult for students, and citizens, to grasp the implications of genetics issues, and to engage in argumentative practices such as critical evaluation of journal or commercial claims about genetics causality. An instance would be the evaluation of genes related to common diseases, explored through genome-wide association studies (GWAS). As Weiss (2009) points out, for most of these diseases, there are many contributing genes, often 20 or more, so even if the effect of one gene (locus) were identified, the aggregate risk effect would be too small to be significant. Understanding random combination of alleles in multifactorial inheritance, and the combined risk probability requires thinking in terms of expected ratios.

Acknowledgement of uncertainty: certainty versus tentativeness/uncertainty is a relevant dimension of personal epistemologies, but here the focus is on its role on the epistemology of genetics. In the local context of genetics causality it is related to probabilism and chance. I propose that this epistemological resource is required, for engaging both in model use and in the evaluation of knowledge claims about genetics. In popular and journalistic accounts of genetics issues, certainty tends to be overemphasized. Federico-Agraso and Jiménez-Aleixandre (2008) have examined the discourse transformations from Hwang's paper claiming having achieved human cloning (later exposed as a hoax), to Journalistic Reported Versions (JRV). The results show an added emphasis on certainty in three of the four journals analysed. An instance, highlighting the role attributed to genome, is the claim about transplants: a sentence in the original *Science* paper stating "these cells would carry the nuclear genome of the patient; therefore *it is proposed* that after direct cell differentiation, the cells could be transplanted without immune rejection" (Hwang et al. 2004, p. 1669, emphasis added), is reported as "theoretically it would allow obtaining all types of human tissues for transplants that the patient would *never* reject." (*El Mundo*, February 13, 2004 p. 30, emphasis added). General public and secondary school students' access to scientific information is mediated by journals, popular accounts or textbooks, so these rhetoric moves shape their understanding of an issue like cloning, influencing their capacity to evaluate it. I will return below to another part of this study, focusing on students' evaluation.

Commitment to consistency of explanations: It should be noted that commitment to consistency is an epistemological resource relevant for all scientific fields. Models explain a range of cases, not just one. In the context of genetics it means that heredity mechanisms are similar in plants and animals, including human beings. In connection with determinism, the focus is on a particular dimension of this resource, the assumption that human beings are subjected to the same biological processes and laws than the rest of animals. This would be necessary to critically evaluate anthropocentric views, an instance of teleological determinism, considering humans endowed with a particular destiny and set apart from other organisms. In a study about students' arguments in genetics (Jiménez-Aleixandre et al. 2000) about the cause for yellow colour in farm chicken, two of the eight small groups, A and E, appeal to consistency, offering examples about humans, as a justification for their claim that the chicken colour was due to inheritance. They rebutted the claim that the colour was due to eating yellow feed of yellow corn. For instance Isa (pseudonym), argues:

Isa: *Well, no* [eating yellow feed is not the cause], *because you, even if you eat a lot of salad, your face doesn't turn green*

In the whole class discussion, Isa and Pat, from groups A and E, engage in a debate with other students who claimed that the cause was either the food or the colour of the farm environment. Isa and Pat appeal to several justifications related to humans, "*if you go out in the field you would not turn green*", "*if you live in Africa, your children would still be white*" and so on. However, two students from other groups, C and G, rebut them arguing that: "*this is comparing chicken to people*" and "*you cannot confuse them*". This means that, for these other students, heredity laws may be different for humans and for chicken.

3.2 Argumentation and the Evaluation of Evidence About Genetics

Argumentation, understood as the evaluation of knowledge claims in the light of available evidence (Jiménez-Aleixandre and Erduran 2008), is an epistemic practice that is receiving increasing attention from science educators. Engaging in argumentation may consist of articulating claims with pieces of evidence, choosing among competing claims in the basis of evidence, or critically evaluating scientific claims and identifying the assumptions behind a claim. The focus here is on the challenges associated with the evaluation of accounts, either determinist or ignoring underdetermination, which, as mentioned above, are prevalent in the media and in some textbooks. In some contexts, the issues involved have social relevance, are socio-scientific, like cloning, genetic engineering, genetic screening. Others relate to social representations, as a claim about differences in intelligence between blacks and whites, stated by James Watson in 2007: "all our social policies are based on the fact that their intelligence [*of Africans*] is the same as ours—whereas all the testing says not really", and "people who have to deal with black employees find this [*the statement that black and whites are equal*] not true" (The Sunday Times, October, 14, 2007).

Students' difficulties to distinguish between claims backed with evidence and other that constitute suggestions or implications are explored in a paper making part of the study about the reception of Hwang's work on human cloning (Jiménez-Aleixandre and Federico-Agraso 2009). We argue in it that the argumentative structure of Hwang's paper is such that its main ostensible claim (the achievement of human cloning), backed with empirical evidence (fabricated, as it turned out later) constitutes a justification for a second claim about its therapeutic applications, for which no evidence is offered. This therapy claim is an instance of ignoring underdetermination, and the long span of years or decades before the potential clinical benefits are achieved, what Magnus and Cho (2005) call the 'therapeutic misconception', claiming that currently there is no such thing as 'therapeutic cloning'.

One of the journal reports was distributed to university students (N = 149), 90 with a biology background and 59 without it. They were asked, first to summarize the JRV in a short essay, and second to write two or more reasons for and against this type of research (they were not asked to state their own opinion, although most did it). The summaries were quite similar for both biology and non-biology students, and more than 84 % of them identified both the cloning and the therapy claim. Regarding their reasons for human cloning, it was found that more than 80 % in both groups appealed to therapeutic applications, despite the absence of evidence about it. Biology students provided more and more sophisticated reasons for cloning, but the most significant differences emerged in the reasons against it. Unspecified ethical concerns were the most frequent, but whilst all non-biology students wrote some

potential reasons against human cloning, there were 20 (22 %) biology students who offered none. Because of the focus of the paper in Jiménez-Aleixandre and Federico-Agraso (2009), we did not have the opportunity to discuss individual responses, and it is worthwhile to analyse one of those who, not only did not offer any reason against human cloning, but also explicitly claimed that they could not find any.

> Student B16 "*It seems to me that this type of research is very positive, mainly by its therapeutic goals, which may benefit us all, (…) for this reason I do not have any argument against it.*"

The argument of this student is interpreted as having a complex structure, where a subsidiary argument constitutes the justification of the main claim. It is summarized in Fig. 3, where implicit elements of discourse are distinguished with parentheses from the student's literal statements.

In this argument, it may be considered that the achievement of human cloning (supported by evidence discussed in the journal report), counts as datum (a) for the student's main argument. However, what is represented as 'datum a' in the figure, again because of its role in the student's discourse, could be rather considered as what Rigotti and Greco-Morasso (2009) in their argument model call *endoxon*, a proposition that has already been accepted by the relevant audience. I suggest that this element of arguments can be useful, in particular in contexts of social relevance. That the purpose of this research is therapy is a claim not questioned by this student, which is not surprising given therapy prominence in the media. This is the main reason underlying the argument and the claim that there are no potential reasons against it.

In my opinion, this is an example of the difficulties that students, and the general public, may have to evaluate genetic pieces of information. Perhaps one of the reasons why a fifth of students with a biology background are not able to give any reasons against human cloning may be related to their perceived professional identity, their self-identification as prospective researchers in biology, promoting empathy toward a research that they perceive as being controversial, and not legal in Spain. On the other hand it is unlikely that

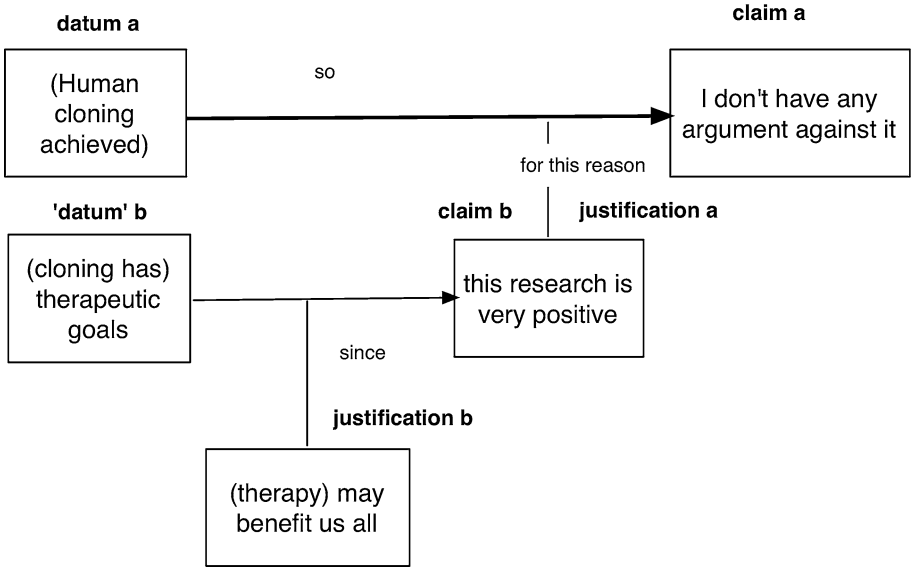

Fig. 3 Argument of a student justifying support to human cloning

they would be unaware of the ethical implications of human cloning. This points out to the difficulties for critical thinking, understood as competence to develop independent opinions and the ability of reflecting about the world around us and of participating in it (Jiménez-Aleixandre and Puig 2012). In our characterization, critical thinking involves being able to challenge the mainstream ideas of one's own group or community, which is a hard task.

3.3 Causality in the Construction and Use of the Model of Gene Expression

Engaging in model building and model revision is an epistemic practice related to the use of evidence, as evidence is used to test explanations and models, and scientific arguments need to articulate relevant theoretical knowledge with evidence. The difficulties experienced by 10th grade students for the construction of explanations acknowledging gene-environment interactions are examined in Puig and Jiménez-Aleixandre (2011). The study involved an analysis of the model of gene expression in textbooks used in the classes participating in it, as well as the most widely used ones in Spain, five in all. The results show that, although four textbooks define phenotype as a result of gene-environment interactions, there is one defining it solely as "*the expression of genotype*". The texts provide only a few examples of environmental influence, and only one of them included an activity requiring the application of the phenotype notion. None of them explicitly addresses biological determinism, although two mention the lack of a scientific base for the notion of human "races".

One of the two teachers taking part in the study did address genetic determinism as part of the teaching sequence about gene expression. The analysis of the discursive moves in the classroom talk between this teacher and his students reveals some obstacles encountered for making sense of gene-environment interactions. When asked to define phenotype, one of them answered that it was "*what is manifested*" and another "*what comes out outside*". When asked to provide examples, they evidenced an identification of 'manifested' not with any trait, but with 'dominant', and so they were not able to offer examples of genotype that would not be manifested different from recessive alleles. The teacher used two analogies and the second one, a music score played by different people, was successful, after what students identified 'environment' as being the influence equivalent to the different players, and were subsequently able to give examples.

We interpret that these difficulties may be related to an implicit causal model that is simple and linear, with each genotype yielding only one phenotype, and to associate epistemological assumptions about causality. This model is more intuitive that the complex causal model of gene expression outlined in the previous section. These findings suggest that this complex question needs to be taught through application in different settings and that a simple lecture is not sufficient. Teaching genetics coupled with development might be useful. However, in most cases, the model of gene expression is just a small part of a lesson and little time is devoted to it.

4 Concluding Remarks

What is the purpose of teaching genetics, of teaching science? Nowadays it is seen as double fold, involving goals specifically directed to genetics learning, including engaging students in epistemic practices, and goals directed to empower students to be critical thinkers, in other words, goals related to citizenship education.

If these are the goals, in the context of genetics, it means supporting students in developing the capacity to understand and evaluate pieces of information related for instance to cloning or genetic screening, and to identify commercial interests that may be entwined with scientific issues in some of these pieces of information.

The argument of this paper is that, for achieving these goals, we need to address reductionism and determinism in biology, and in particular in genetics. Given the social role of science, authors such as Looijen (2000) suggest that we might even say that reductionism is the dominant ideology of our society. Considering the prestige and high scientific status of genetics nowadays, genetic determinism is rarely questioned, outside the works of philosophers of science and some particular scientists. "The cause is in the genes" is a final word in public discourses, and sometimes also in scientific discourses, even outside genetics explanatory domain.

When teaching genetics, we cannot assume that probabilistic explanations and causality involving causes producing multiple alternative effects are unproblematic. The difficulties involved in its appropriation by students need to be explicitly tackled. In order to do so, students should engage in using these models and explanations in different contexts, in evaluating knowledge claims against evidence, as opposed to being lectured. This engagement needs continuous scaffolding from the teacher.

In my view, engagement in epistemic practices is one way to support the development of more sophisticated epistemologies, and it can be more fruitful than domain-general consensus views. As Duschl and Jiménez-Aleixandre (2012) point out, developing epistemic criteria and evaluating the epistemic status of ideas are elements from learning environments that seek to achieve goals related to the nature of science.

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