Structural Distinctions: Entities, Structures, and Changes in Science

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I argue that the pessimistic meta-induction (PMI) seems to point an ontological priority of the relations over the objects of the scientific theories of the kind suggested by French and Ladyman (2003). My strategy will involve a critical examination of epistemic structural realism (ESR) and an historical case-study: the prediction of Zeeman's effect in Lorentz's theory of the electron.

1. Introduction. The following is intended to take a stand in the debate on Structural Realism in favor of Ontic Structural Realism (OSR) as recently defended in French and Ladyman (2003). In particular I argue that the pessimistic meta-induction (PMI) seems to point an ontological priority of the relations over the objects of the scientific theories. My strategy will involve a critical examination of epistemic structural realism (ESR) and an historical case-study: the prediction of Zeeman's effect in Lorentz's theory of electron.

2. Access Denied: Epistemic Views on Structural Realism. The aim of ESR is achieving a realist position that brings together the no miracle argument (NMA) and the pessimistic meta-induction (PMI), providing a realist answer to historical changes in the science. As far as the theoretical level is considered, theories undergo a series of changes. Even if taken with some qualification, theory change is the report of a series of historical facts. In the history of science we have an impressive list of entities once

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effective and useful for the scientific enterprise and successively replaced (Laudan 1981); therefore success is not a sufficient ground to believe in entities. In other terms, PMI seems reasonable simply because these changes prevent us from concluding that such entities really exist, no matter the level of empirical success that the theory has achieved. Nonetheless, even the success of science cannot be denied, in particular when the predictiveness of theories is considered. If we can predict phenomena somehow not taken into account when the theory has been formulated, then it is plausible to consider the theory approximately true (Worrall 1989, 102). Otherwise the novel prediction seems miraculous, indeed. The advocate of ESR argues that both these points can be addressed if we take PMI as expressing a limit on our capability to know reality. This limit does not apply to the whole abstract level of the theory.

The analysis of the history of electromagnetism provides matter for a qualified distinction. Although the notion of ether is abandoned in the shift between the two frameworks, Fresnel's equations can be retrieved within Maxwell's electromagnetic theory. This seems to provide evidence in favor of the idea that the shift does not involve the equations, the structural elements of the non empirical part of the theory (Worrall 1989, 117). Then, even if we have to concede to the antirealist on the entities, we can be realist about the formal features of theories, and the predictiveness of physics finds a non-miraculous account:

> Fresnel completely misidentified the *nature* of the light, but nonetheless it is no miracle that his theory enjoyed the *empirical predictive success* that it did; it is no miracle because Fresnel's theory, as science later saw it, attributed to light the right *structure*. (Worrall 1989, 117; second italics mine)

Prima facie, it seems that we can explain the success of science as well as its deep changes by observing that theories attribute to the world a structure, represented in the case of physics by the mathematical device, and a nature, represented by the entities.

Let us see where this distinction leads us. The reference to the predictive success of Fresnel's theory insists on the correctness of the representation of the structure of light provided by the equations. We cannot know if the hypothetical entities of our theories do exist or not, but "these equations express relations, and *if the equations remain true, it is because the relations preserve their reality*" (Worrall 1989, 118; italics mine). Therefore the occurrence of the equations in different frames depends upon their truth. Hence, for the claim to make sense, the structure cannot be merely a formal device. The equations represent something in the world; they have physical content and are committed to the existence of the relations they represent. It can be the case that what a theory tells us about the entities in terms of their fundamental properties corresponds to reality, but establishing this goes beyond the power of our knowledge.

Psillos noticed that as far as the distinction is epistemically grounded there seems to be a problem for ESR. The problem, as Psillos put it, corresponds to establishing what exactly we can know about reality, i.e., what features the structure has. He explores three possible ways in which the distinction can be formulated and consequently the content of our knowledge captured:

(A) We can know everything but the individuals that instantiate a definite structure; or
(B) We can know everything except the individuals and their first order properties; or
(C) We can know everything except individuals, their first order properties and their relations. (Psillos, 2001, S19)

Considering in particular Poincaré's quotation, it seems to me that ESR is committed to something close to case (B); I will justify and qualify this claim in a while. I generally agree with Psillos that if ESR corresponds to (C) there is no difference with a form of Russellian (or Maxwellian) structuralism which in turn can hardly be considered a form of realism. Now let us see Psillos' argument on this option. Psillos concludes that if ESR corresponds to (B), then the difference with standard realism would be only of degree since ESR would amount to a

> Carnapian relation description . . . [that] describes an object as that which stands in certain relations to other objects . . . . Although relation descriptions do not entail *unique property description* they do offer some information about an object, because, generally, they entail *some* of its properties. (Psillos 2001, S20; first italics mine)

The general conclusion Psillos draws is that there is no natural epistemic cut between relational and first order properties. In other words, if we believe in the structure we have no reasons to doubt the entity and its properties, because they form an epistemic continuum. But do they really form a continuum even in this sense? Let us assume that ESR corresponds to the claim that only the relational description captured by the equations of the theory is a reliable theoretical element. A relation description does not entail a unique property description; therefore it can be multiply realized; i.e., it defines a class of *realizers* that can deeply differ one from each other in terms of fundamental properties—but in this case the continuum between structure and entity seems broken. Multiple realizability involves an ignorance in principle that standard realism cannot accept,[1] but this feature seems to fit nicely with the agnosticism towards the entity and its properties wanted by the advocate of ESR. It can be the case, for instance that from a relational description of electromagnetic forces we can infer properties like the mass or the charge of the electron. But the whole point of PMI is that there is nonetheless room to doubt if the properties and the entity have been replaced so frequently in the past. In other words, which electron is the bearer of the values of mass and charge we inferred? The classical electron? The quantum electron? The classical particle of Lorentz or the spinning quantum-relativistic point mass of Dirac? Notice that one aspect of the theory-change issue in the case of electron is that not all the properties of these 'electrons' are compatible one with each other. This last observation recalls the original aim of ESR, i.e., to individuate a theoretical feature resisting through the changes. At this point the characterizations provided in (B) needs some modification. To address PMI realistically on the basis of the structure as a stable element of our knowledge involves a conception of structures as *independent* from the entities and their properties. Our knowledge of the structure remains stable despite the fact that the entities and their properties change; therefore the knowledge of the structure concerns relational, extrinsic properties, properties that are not intrinsic to the entities. In a while I shall introduce a more rigorous definition of what is meant here for the distinction between intrinsic and extrinsic, but let me stress a consequence of this independence. If the content of the equations includes existing extrinsic properties and relations, then the novel prediction of a theory must find an explanation in the relational content of the theory itself; otherwise it turns out to be inexplicable why we keep retrieving the same equations in each different framework dealing with the same class of phenomena to which the original prediction belonged. The historical case introduced in the next section is concerned exactly with this requirement. I will show that in the case of the prediction of the Zeeman effect performed in the framework of Lorentz's theory of electron, an intrinsic property of the electron, namely its character as a rigid body, is essential to perform the prediction. This intrinsic property, by the way, does not feature in successive theories of the electron.

Let us conclude by introducing a definition of intrinsic to spell out the distinction between intrinsic and extrinsic. In the following I borrow the definition provided by Langton and Lewis (1998). The definition does not capture the whole class of intrinsic properties; rather, it focuses on the so called basic ones. I will not address here the related issues. What is im-

1. David Lewis (1970) argues against multiple realizability as an unacceptable feature for standard realism in the case of Ramsification.

portant for us is that with some qualification, the definition provides a useful characterization of what should and what should not feature in the structure for ESR to make sense.

> The basic intrinsic properties are those properties that (1) are independent from accompaniment or loneliness; (2) not disjunctive properties; (3) not negations of disjunctive properties. (Langton and Lewis 1998, 120)

It is helpful to see this definition in the context of duplication. A property is intrinsic if it can never differ between two perfect duplicates. More intuitively, but with the abovementioned qualifications, a property is certainly intrinsic if an object has the property no matter if there is nothing else or other things in the world apart from it. A *purely extrinsic* or relational property at this point is a property that a thing has "solely in virtues of how accompanying things, and its external relation to these accompanying things, are" (Lewis 2001, 384).

As far as I can see being a classical particle or a rigid body is an intrinsic property. Let us come to the contribution of the historical case.

3. Predicted Interferences.

3.1. An Old Faraday Idea. From 1891 to 1897, Pieter Zeeman carried out a series of experiments in Leyden under the supervision of both Kamerlingh Onnes and Lorentz. In particular, he was looking for an interference between the electromagnetic field and the frequency of light. Lorentz, in the same period, was after a unified theory of matter, light and electromagnetism. But Zeeman's interest referred to Faraday's old project based on the observation that a magnetic field modifies the way in which light is propagated and reflected and therefore it is very likely to modify its frequency. Faraday attempted unsuccessfully to detect such an interference. According to Zeeman, that failure depended on the low quality of Faraday's equipment, and in his notebooks he observes that "it might worth while to try the experiment again with the *excellent auxiliaries of spectroscopy equipment of the present time*" (Kox 1997, 140; italics mine).

Notice that when he started his experiments, the available theories suggested that the interference was not detectable at all.

In the fall of 1896, the assumption of Zeeman turned out to be right. A widening in the spectral lines of the light of Sodium emitted in a magnetic field was detected. Lorentz predicted that the widening depended on a splitting of the spectral lines. The splitting was observed in a successive phase. The theoretical explanation was based on mechanical application of the Lorentz Force. Before getting into the details of experiments and related predictions, let us explore the general picture of the phenomena peculiar to Lorentz's theory.

3.2. The Dutch Synthesis: Charged Particles within Maxwell's Electromagnetism. Theoretical physics at the moment in which the new phenomenology appeared was concerned with an account of the relation between ether and matter. Maxwell's electromagnetic theory was dramatically successful but nevertheless incapable of accounting for phenomena like optical dispersion, the magneto-optical effects discovered by Kerr and Faraday, the high transparency of metal sheets to light, and electrolysis. All of this required a clear understanding of the microstructure of matter, electricity, magnetism and light, possibly a unifying theory. Maxwell's electromagnetism was silent on this issue (see Arabatzis 2001, 176). Precisely these concerns inspired Lorentz's *memoir* of 1892, the contribution in which the Lorentz force was formulated. The framework was based on a dualist ontology designed by combining the ontological independence of the charge from the ether with the idea that any electromagnetic phenomenon is a form of disturbance in a medium.[2] The resulting picture represented the common microphysical structure of matter, electromagnetism, and light in terms of the dynamic of charged particles perturbing the ether. Their electric charge aside, particles were classical rigid bodies. Maxwell's framework became the theory of ether and the electromagnetic processes had to obey to Maxwellian constrains. *The charged particles were supposed to be the only kind of matter interacting with the ether*, and since the interactions were essentially electric in nature, the medium itself was completely stationary. Further, the framework embedded a notion of local time and the first formulation of Lorentz's transformations.

The theory was presented as a combination of six hypotheses from which the fundamental laws were derived. It is worth exploring these hypotheses because they provide a description of the properties of ether and charged particles, thus giving a clear clue to the kind of picture Lorentz had in mind.

(i) "Charged particles have inertial mass and weight. The charged particles are in part mechanical bodies to which the laws of motion apply"[3] (McCormmach 1970, 459).

2. For the problems left open by Maxwell theory see Buchwald 1985, Darrigol 1994, and D'Agostino 1973.

3. Here and in the following passages I'm quoting Lorentz's memoir in the translation offered in McCormmach 1970.

(ii) "[The theory] identifies potential energy of an electromagnetic system with its electric energy, which is, in electromagnetic units,

$$2\pi \int (f^2 + g^2 + h^2)d\tau, \tag{1}$$

where f, g, h is the dielectric displacement at each point of the ether. The dielectric displacement satisfies

$$(\delta f/\delta x) + (\delta g/\delta y) + (\delta h/\delta z) = 0 \tag{2}$$

outside the charged particle, and

$$(\delta f/\delta x) + (\delta g/\delta y) + (\delta h/\delta z) = \rho \tag{3}$$

inside, where ρ is the density of electric charge" (McCormmach 1970, 464).

From (i) and (ii) the potential energy of an electromagnetic field is defined as electric energy and this turns to be related to the dielectric displacement in the ether. The dielectric displacement must satisfy (3), i.e., a condition on the conservation of the density of charge at any point of the displacement. Notice that this suggests a deep interplay between the mechanical and electrical features of the theory, since the conservation of charge density is 'localized' in the particle. Broadly speaking, the charge carrier plays the fundamental role in the picture and the charge carrier is a mechanical entity. Here the ether, the location of the electric interaction, is completely characterized in terms of electric energy. This corresponds to attributing to the ether only electrical interactions with charged particles.

(iii) "[C]harged particles behave like rigid bodies; moreover, each point of a particle preserves the same value of ρ, whatever its motion" (McCormmach 1970, 464).

(iv) Define as follows "the total electric current u, v, w as $u = \rho\xi + (\delta f/\delta t)$, $v = \rho\eta + (\delta g/\delta t)$, $w = \rho\zeta + (\delta h/\delta t)$, where ζ, η, ξ is the velocity of a given point of a charged particle" (McCormmach 1970, 464; the u, v, and w are the vectors of the total current).

Before we move on to the laws of the theory, let me emphasizes some peculiarities.

First of all, (i) and (iii) define the particle as a rigid body with mass and weight, equipped with an electric charge whose density has to remain constant during motion. These mechanical properties will turn out to be crucial in the analysis of the Zeeman effect.

Further, the above four hypotheses provide an immediate element of continuity with Maxwell's theory since they allow one to retrieve the notion of currents as incompressible fluids. The incompressibility of currents was obtained in that framework, treating the currents as the result of a strain in the ether surrounding the conductor (Darrigol 1994, 285). In the new theory the currents are due to the motion of charged particles whose charge density is conserved during the motion, and thus are incompressible.

Let us come back to the hypotheses.

(v) The kinetic energy of the system is defined in terms of magnetic energy and it depends upon the total current.
(vi) "[T]he location of each point of the ether participating in the electromagnetic motions of the system is determined by the positions of all of the charged particles and by the values of *f*, *g*, *h* at all points in the ether" (McCormmach 1970, 465).

Adding to these assumptions D'Alembert's Law, it is possible to derive the equations of motion in the ether. Let us come to the most important contribution of the theory, the equations of the Lorentz Force. In the following , V is the speed of light, f, g, and h describe the dielectric displacement at each point in the ether, ζ, η, and ξ represent the velocity of a given point of a charged particle, and α, β, and γ represent the magnetic force:

$$X = 4\pi V^2 \int \rho f d\tau + \int \rho(\eta\gamma - \zeta\beta) d\tau,$$
$$Y = 4\pi V^2 \int \rho g d\tau + \int \rho(\zeta\alpha - \xi\gamma) d\tau,$$
$$Z = 4\pi V^2 \int \rho h d\tau + \int \rho(\xi\beta - \eta\alpha) d\tau. \quad (5)$$

Lorentz derived these equations mechanically; they described the force acting on a particle with charge density ρ moving in the ether. In particular, the first integral on the right side represents the electrostatic force, whereas the second integral expresses the force acting on single particle moving through the ether. It is interesting to notice that Lorentz could derive Fresnel coefficients from his system of equations (McCormmach 1970, 465–467).

The mechanical approach not only seems to provide a reasonable basis for the searched unification but also from the very beginning saves all the preceding relevant results. Let us now examine the kind of explanation performed by this framework in the case of Zeeman's discovery.

3.3. The Interference Detected. In the fall of 1896 Zeeman put a piece of asbestos soaked with common salt and exposed to the flame between the arms of a Rumkorf magnet. A Rowland grate provided the analysis of the line spectra. He described as follows what he was able to detect:

> If the current was put on, the two D-lines were distinctly widened. If the current was cut off, they return to their original position. The appearing and disappearing of the widening was simultaneous with the putting on and off the current. (Zeeman 1897, 227)

So, the first outcome was a widening in the lines of the light emitted by the sodium. It is important to observe that no splitting of the lines was found at this stage. Zeeman himself informed Lorentz of the outcome and officially reported the result to the faculty. Two days later, Lorentz communicated his account. His model resolved the broadening of the lines in a more complex pattern of splitting, and described accurately the structure of each line. In this sense, the explanation was a prediction of an unobserved phenomenon.

3.4. The Analysis of the Pattern of Interference. The model provided is based on the Lorentz Force but the notation below is due to the new vectorial formulation that Lorentz obtained for (5) by the end of 1895:

$$K = e(E + vH/c)(I),$$

where H and E are respectively the magnetic and electric field and e and v are the charge and mass of the particle (Lorentz [1895] 1935–1939).

Let z be the direction of the field H; then the equations of motion for a charged particle rotating around the centre of the atom, once a magnetic field is applied, are

$$m[(d^2x)/d(t^2)] = -kx + [(eH)/C][(dy)/(dt)], \tag{6}$$

$$m[(d^2y)/d(t^2)] = -ky - [(eH)/C][(dx)/(dt)], \tag{7}$$

$$m[(d^2z)/d(t^2)] = -kz. \tag{8}$$

The general solution of (8) is

$$z = a\cos(\omega_0 t + p), \tag{9}$$

with a and p constants and the frequency $\omega_0 = 2\pi(k/m)$.

At this point is possible to derive two solutions for each of (6) and (7)

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by means of which two more values of frequency are obtained:

$$\omega_1^2 = \omega_0^2 + [(eH)/(mC)]\omega_1,$$

$$\omega_2^2 = \omega_0^2 + [(eH)/(mC)]\omega_2,$$

where ω_0 is the unaltered frequency, since z is both the direction of the light and the direction of the field H (Kox 1997, 142).

From the mechanical point of view, the model treats the electron as an harmonic oscillator; this is what is expressed in the equation (6), (7), and (8), if we ignore the electromagnetic terms added in the extreme right side in (6) and (7). Once a magnetic field is applied, the particle experiences a Lorentz force and the period of its motion is altered according to the relations expressed by the electromagnetic terms, i.e., a rigid body moving of harmonic motion to which is applied a force. More generally the idea is that the electric ion is responsible for light emission. It has an oscillatory motion with arbitrary direction in space. This motion can be resolved in three oscillatory components of the same frequency: a linear oscillation and two circular oscillations, the two circular being one clockwise and the other anticlockwise. When a magnetic field is applied because of Lorentz's force acting on the ion, we have two different outcomes, both depending upon the direction of the detection.

(a) If the direction of detection is parallel to the direction of motion of the particles we have the pattern of splitting described above: two lines one broader than the other since the component in the direction of the field remains unaltered. The two lines observed together are wider than the line in absence of the field, i.e. precisely Zeeman's first observation.
(b) If the direction of detection is perpendicular to the direction of the motion of the particle a "triplet" is supposed to be detected. The pattern of interference has to involve the three component, with three plane polarized lines. The middle component has to have a direction parallel to the field and the other components have to maintain a direction perpendicular to the field.

This is exactly what Zeeman detected in a further experiment with the blue line of Cadmium, and this was not the only result (Kox 1997).

3.5. The Ratio e/m of the Electron. Once the model had allowed one to calculate the alteration in the frequencies, the terms in the system of equation above were all corresponding to known values and therefore extracting the ratio e/m of the particle was just a matter of calculation:

If the change of the period is represented by δT, then [with

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$\delta(1/T) = -\delta T/T^2$] the positive or negative change of T is given by:

$$\delta T = (H/4\pi)(e/m)T^2. \quad (3)$$

> If δT is measured during the experiment, and H and T are known, the ratio e/m of the electron may be determined by the aid of formula (3) . . . . From the measured widening by means of the equation (3) the ratio e/m may now be deduced. It thus appears that e/m is of the order of magnitude 107 [*emu/g*]. (Zeeman 1913, 35)

Interestingly, the expectations were not towards a *new* constituent of matter but rather it was expected to find evidence in favor of the assumption that the charged particle was a Faraday's ion, which would lead to a broad unification of the field (Kox 1997, 142).

Notice that the value of e/m is interpreted in strict relation with the notion of particle as rigid body since it is taken to provide an estimate of the size of the particle.

4. Conclusive Remarks. This story has an interesting and complex follow-up that I cannot discuss here in detail. What is worth noticing is that, generalizing this result, Larmor, a few months after this discovery, derived his precession formula:

$$P = (2/3)(e^2a^2/c^3),$$

where a is the acceleration of the electron, e is the charge and c is the velocity of light. This formula is a relation that gives, in the case of Zeeman's interferences, the amount of energy released by an electron subjected to acceleration. This relation is still derived today in the quantum theories and is extremely important in the study of nuclear magnetic resonance (Warwick 1993, 56–57).

From every point of view, this case meets the requirements that the advocate of ESR wants. We deal with a theory that provides a strong prediction that eventually delivers to the successive theories stable theoretical contents. Nonetheless the epistemic role of some intrinsic property seems unavoidable. It seems that neither Psillos nor Worrall are right. It seems that realism is still in trouble with regard to theory-change. But let us observe the role played by some of the relations mentioned in this historical case. The Lorentz framework retrieves the incompressibility of currents of Maxwell's theory and Fresnel's equations. It seems that the new electron is designed to meet both empirical needs—accounting for the Kerr effect, the Faraday effect, electrolysis, high transparency of metal sheet—and precise theoretical relations secured by the preceding successful science. The properties of the classical particles meet all the requirements, and their design is impressively powerful and effective from the epistemic point of view. Further, the role they play in allowing the prediction prevent us from dispensing with them epistemically. There is nothing we do not know about them. Nonetheless, they will disappear in further theories, and therefore they seem to be essentially theory-dependent. On the other side, relations can hardly be taken less than realistically, since they are both independent of the framework in which they are achieved and epistemically effective. It seems that a "form of realism adequate to the physics needs to be construed on the basis of an alternative ontology which replaces the notions of objects . . . with that of structure in some form" (French and Ladyman 2003, 37).

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