Mind & Society 3 (5) 2002, pp.93-109

Discovering relativity beliefs: towards a socio-cognitive model for Einstein's Relativity Theory formation

Andrea Cerroni

The research on which the present paper makes a point is aimed at designing a cognitive model of Albert Einstein's discovery that is based on fundamental Einstein's publications and placed, ideally, at a meso-level, between macro-historical and micro-cognitive reconstructions (e.g. *protocol analysis*). As in a *cognitive-historical analysis*, we will trace some discovery heuristics in the construction of representations, *that are on a continuum with those we employ in ordinary problem solving* (Nersessian 1992).
Firstly, some theory-specific, reflexive heuristics - named *orientative heuristics* - are traced: *inner perfection*, *explain-or-assume*, *explanatory correspondence*, *and covariance/invariance*. Then, other well-known *abstractive heuristics* as *analogical* and *imagistic reasoning*, *thought experiment*, *limiting case analysis* (e.g. Nersessian 1992) are shown occurring in Einstein's key-publications. A sketch of a socio-cognitive model for his discovery is then presented following two suggestions: (a) an idea of van Fraassen about *discovery phases*, and (b) the Humean distinction between *beliefs* and *ideas*.

1. Orientative heuristics

Generally speaking, heuristics are very general, cognitive instruments on which the scientist relies in organizing and orientating his own search path. Even though at times scientist shows he "feels" them strongly, they are however always *weak,* since they do not guarantee the outcome of a solution (whatever it can be), nor do they prevent errors. We distinguish the heuristics found in the bulk of Einstein's reasoning, as it is reported in his published work, into two very different typologies: *orientative* heuristics and *abstractive* heuristics. Before starting with orientative ones, it is worth noting that these heuristics are not logical requirements, i.e. they don't state any *necessary* condition. They are just *orientative* criteria to be managed by an overall, Simonian, satisficing rationality, that indeed can be thought of as another cognitive heuristics. Analogously, abstractive heuristics are not rigorous algorithms.

1.1. Inner perfection

In Einstein opinion, a "good" theory enjoys what he calls *inner perfection* (Einstein 1949). He talks about a *musicality in the field of thought*: the simpler the premises of a theory are, the more various the things it links, the more extensive its field of application is, the more convincing it is. Over and above value judgments and theory choice criteria, as in (Kuhn 1977), *aesthetic* considerations, far from being a threat to the rationality of science is, on the contrary, a key element for the construction of the reasoning which leads the scientist towards a discovery (McAllister 1996). To be more specific, *inner perfection* has a double value: a Machian, *cognitive economy*, and a theory *compactness and rigidity* (Einstein 1936). The last one states that if just one building block of relativity theory would be proven false, the entire theory would collapse.[1] Both values are directed to the theory as a whole, not to each part of it. In particular, what is true for *physics* is not necessarily true for *mathematical* means (that can indeed be very complex).
If this analysis is correct, we can hypothesize, behind the heuristic, a more fundamental belief in a rough, nature's simplicity (e.g. Einstein 1933 and 1949), leading Einstein to remove as many conflicts, asymmetries and defects as he is able to point out in current physics.

So, *inner perfection* will enter our cognitive model for Einstein's discovery as playing two roles: as an heuristic on the same level of the others, and also as an overall guide for managing all other heuristics.
Exemplar uses:

- *asymmetries* in electrodynamics (of moving magnet & conductor) between different explanations, not inherent to phenomena (Einstein 1905);
- *conflict* between Galileo's relativity and invariance of Maxwell's equations (Einstein 1905);
- *redundancy* of luminiferous ether (Einstein 1905);
- *no explanation* for equal falling of all bodies in the gravitational field (Einstein 1911);
- *inherent epistemological defect* of classical mechanics: the *privileged space* of Galileo is a merely factitious cause and not an observable thing (Einstein 1916);
- complicated mathematical apparatus (*covariance*) of gravitational field equations in order to gain *simpler and more natural* physical suppositions (Einstein, Infeld 1938);
- search for a *theory of principles*, rather than a constructive theory (Einstein 1948).

1.2. Explain-or-assume

Einstein seems to be using as a cognitive heuristic the following "principle"[ii]: *do not consider as casual those regular connections among phenomena perceived or described as distinct* (Petroni 1990; see also Zahar 1973 and 1989). The heuristic is applied to *apparently* casual coincidences that the existing theory finds in a visible manner and consists in the attempt to explain it as *caused* by some general principle of the theory. Moreover, for an evidence that is considered enough "strange and relevant", after repeated failures in the search for a (satisficing) explanation, a sudden decision intervenes, drastic and at times courageous on the part of the researcher: he assumes that evidence as a true principle inside the mutating theory, by making the hypothesis that *there must exist a profound reason for such a coincidence* (Einstein 1936) though so far unknown. So, the heuristic aims at reducing (eliminating) the *over-determination* of theory by data, i.e. its *incompleteness* (Mamchur 1987).
The activation of the heuristic takes place in three stages:
(a) the focused evidence is transformed into *conjecture*;
(b) such conjecture is thus transformed into a *principle* that is postulated as the basis for a new theory (theory mutation);
(c) from this principle, possible and theoretically relevant *consequences* are deducted which are especially experimentally identifiable.

However, it is patent the non-logical nature of this heuristic: for example, if light speed constancy has to be treated as a principle, its exact value still remains a coincidence without any explanation at all. The difference is just matter of relevances *believed* by scientist.

Exemplar uses:

- no Earth motion relatively to light medium → no ether exists (Einstein 1905);
- constancy of the velocity of light *in vacuo* → *light principle* (Einstein 1905);
- experimental equivalence between inertial mass and gravitational mass → *equivalence principle* (Einstein 1911).

1.3. Explicative correspondence

As it is now widely documented, a heuristic inside the so-called "mature sciences" is a rule-of-thumb interpretation of the *principle of correspondence*.[iii] So, we can establish the *generalized principle of correspondence* as following (Fadner 1985): *the equation of any new theory must*

transform, with appropriate accuracy, into the correspondent equations of a previous, well established theory where this is well sustained by data.
Not only does any limitation highlighted in a theory suggest the way for its immediate overcoming: one of the first steps in order to derive the theory and attribute a physical interpretation to its theoretical terms consists in keeping the old, well established theory, as still valid under limit conditions. Einstein writes (1921): *in order to decide whether equations are in accordance with experience, it is in the first instance necessary to examine whether, in the first approximation, they lead to the Newtonian theory*.
As Achinstein notices that the concepts that appear in Bohr's theory are strictly related to those of classical electrodynamics (given the definition of terms and the determination of the values of measures), we can as well notice that those in Einstein's theory are also strictly related to the terms in Newton's theory (both dynamics and gravitation theory). In our case *it is indeed predictable how the term will be used in the new theory considering the way it is used in the old one* (Achinstein 1968). As there are some features or elements of the old theory not perfectly fitting into the rest of the theory and pointing to the new theory, we can conclude that Relativity Theory has *footprints* on Newtonian Theory (cfr. Post 1971), pace Kuhn and Feyerabend.
Getting closer to this heuristic, we can also point out a double semantic flux between the new and the old theory:

(a) the old theory is, at the moment of the discovery, a constant reference, not only with the aim to guarantee some accordance with experience, but also for the assignation of meanings to new words, and thus for the redefinition of concepts;

(b) it is also evident that the new theory does in fact reinforce the old one and the whole theoretical framework too, through an *explicative deduction*. The old theory receives an *explicative support* which adds to the one it possessed before the new theory emerged, as this is in some way a guarantee for its projection outside of its original and effectively controlled domain. Moreover, there is a new *inter-theoretical support* coming from other theories with which now old theory is possibly coherent.

If our analysis is correct, the explicative framework, which holds the theoretical construction together, increases in *explicative coherence* after *explicative correspondence* is applied.

Exemplar uses:

- Galilei & Lorentz transformations (Einstein 1905);
- General Relativity and Newtonian gravitation (Einstein 1916);
- General Relativity and Special Relativity (Einstein 1916).

1.4. Covariance/invariance (methodological relativity)

The main defect of pre-relativistic mechanics, according to Einstein, was yet of a purely philosophical nature: it was unable to reconcile the *variability* of the descriptions of phenomena provided by different observers with the existence of *universal* laws independent from the observer himself. This is, to put it so, *Einstein's problem*: to find a theory that could satisfy this epistemological prerequisite.[iv]
He reasons according to the following ideas:

(a) each theoretical quantity has to be written in a *co*-variant form, that is using *tensors*, kind of mathematical object whose components vary, from one system of reference to another one, in exactly the same way in which the measures of the (differentials of) observer's system coordinates vary. This first prerequisite can be called *co-variance*, along with Reichenbach (1927);

(b) the relationship among theoretical quantities has to be put in an equation that remains *un*-changed every time a system of reference is replaced by another one. Along with van Fraassen (1989) this prerequisite is a kind of generality that can be called *in-variance*.

As a consequence of the application of this double heuristic rule onto physical theory, every observer, though involved in apparently different phenomena, will be allowed to find exactly the same equation: and this, according to Einstein, is a prerequisite for that equation in order to be able to express a fundamental regularity of nature. But to go on this path, we now need a theory about subject-object connection, i.e. about measuring: rods and clocks have to be represented as solutions of the basis equations, and not as it were, as theoretically self-sufficient entities (Einstein 1949). In methodological terms, we can join Reichenbach (1928), concluding that we can get rid of observer's relativism just through the conscious awareness of the concrete role that subjectivity plays in our research methods.

All in all, *covariance* must be such as to make it possible that the substitution of a system of reference with another is a symmetry for the law, so as to leave unaltered the essential or relevant structure of the problem. This is the condition, indeed, for having essentially the same solutions in whatever system, and thus the laws expressed in them do not appear as distinct laws, but are rather re-conducted to a more general one (van Fraassen 1989). We thus talk of *invariance under symmetry*. Anyway, we are dealing with a heuristic rule, grounded in Einstein's deep beliefs, and not with an inflexible, logical request for the adequacy of hypotheses, as the two steps (Special Theory in 1905, and General Theory in 1916) in Einstein's relativity discovery testify.

Exemplar uses:

- *principle of relativity* firstly stated in (Einstein 1905);
- *symmetry* between systems of reference with uniform acceleration and homogeneous gravitational field (Einstein 1911);
- *principle of general covariance* (Einstein 1916).

2. Abstractive heuristics

Nancy Nersessian (1992) defines as *abstractive techniques* four types of heuristic reasoning very widespread in the scientific research, especially in its "revolutionary" phases They are: *analogical reasoning, reasoning by images, mental experiment and analysis of limit cases*. In them the imaginative component is dominant, while the linguistic and propositional one is of secondary relevance. Perhaps, it is even impossible to transform them into algorithmic instruments, since it is not easy to reduce them into codified sequences of calculations: it seems calculations can be done only *after* the heuristics have been adopted to constitute the elements to be calculated. Finally, we are dealing with cognitive techniques which support inductive reasoning, and whose cognitive efficiency (production of controllable hypotheses) and cognitive efficacy (production of deductively certain knowledge) are uncertain.

2.1. Analogical reasoning

A general schematization of analogical reasoning is the following: if we know that A and B share some properties $p_1 \ldots p_m$, reasoning by analogy we check if B as well has another property p_n, which we know is possessed by A (Hesse 1966). An inference of this kind is however weaker than a usual inductive inference, since it is generally based on inaccurate similarities. It is indeed thanks to this inaccuracy that the analogy proves to be usable to build new hypotheses, even when we have only very few elements available. Thanks to it, we go beyond the knowledge we possess of a certain domain, resorting to the knowledge (considered as better) we possess of another. Yet, in order to transfer the knowledge of the domain *source* to the domain *target,* the analogical process must focus on a structure of relations between the components of the domain *source* and keep it unvaried after a *mapping* (which for this reason is defined as *isomorphic*) on the *target* (Gentner 1989). The transferred knowledge, thus, regards *systems of relationships*.

We must however always operate a final substantial modification, a *re*-representation, so that we can supply the interpretative key to exactly establish what are the element which are actually linked by the transferred structure, taking thus into account the specific boundary conditions in the new domain. This can entail a heavy *re*-interpretative intervention on the part of the scientist, which can force him to struggling against his (and our) most *inveterate habits* (Einstein 1917).

It is however appropriate to make some considerations.

With an analogy we create an *abstract* link relatively stable between two heterogeneous domains, which is reusable as a *scheme*, and thus becomes a part of the cognitive resources available to the

scientist. He can later go back to it again, in order to face other problems. In addition, in relation to heterogeneity, or *cognitive distance*, of the linked domains, we can find "lengths" of the *mapping* even very different for different analogies.
However, contrary to what would happen in a logic-linguistic model of analogy, it is worth noting that an analogical reasoning is actually able to produce *new* knowledge: in the first instance for the new links it establishes among domains, and then for the consequences of *mapping* on the domain *target*.
Analogies are often present in the reasoning, which leads to scientific discoveries,[v] and Einstein, in particular, sometimes borrows from the "cognitive archive" of the history of physics and mathematics, solutions found for scientific problems which he considered somehow *analogou*s to his own.
Exemplar uses:

- analogy between *space and time*, from which he draws the notion of space-time (thanks to Minkowski's contribution as well) (Einstein 1905);
- analogy between *three-dimensional and four-dimensional systems of co-ordinates*, first in a four dimensional space-time and then in Gaussian generalized co-ordinates (Einstein 1905 and 1916);
- analogy between *Maxwellian's field equations* and gravitation equations (Einstein 1916);
- analogy between non-existing *perpetuum mobile in thermodynamics* and principle of relativity (Einstein 1949);
- analogy between *Maxwell field theory* and gravitation theory;
- analogy between *Gaussian theory of surfaces* and mathematical problem of General Theory.

2.2. Imagistic reasoning

A kind of analogical reasoning that is particularly abstract and simplified, now well studied by cognitive sciences, allows us to visualize a certain structural relationship and to carry out calculations on it (Kosslyn 1983), giving a *perceptive correlate of a mental model, considered from a precise point of view* (Johnson-Laird 1983). The role of this kind of reasoning probably resides in the easy way in which our mind builds inferences of a perceptive kind, which in this case provide a level of abstraction ideally intermediate between, for example, phenomena on the one side, and mathematical formulae on the other.
This kind of reasoning allows a partial "memory downloading" and facilitates the public communication of our own internal representations and in general the process of learning (Nersessian 1992). We are thus dealing with a very useful cognitive instrument, which is often used also in scientific research (Mach 1905; Hadamard 1945; Miller 1984; Finke *et al.* 1992). And Einstein too systematically resorts to it. In particular, when he retrospectively broods over his work, and especially with historical and popular aims, he resorts to very creative reasonings, which are characterized in visual terms, with the explicit aim at *fixing ideas*.
At this stage we could legitimately wonder whether Einstein uses these images just for popularization and rhetorical aims (*context of justification*), or as real heuristic instruments (*context of discovery*). Even though we cannot provide a definite answer, and since there is no reason to exclude aims of the first type, we however have some evidence of their effective importance of the second type too. Einstein himself speaks about the relevance of visual thinking in his own scientific reasoning (cited in: Wertheimer 1959). In addition, when Einstein wonders what *precisely thought is*, he argues in favor of the centrality of imagination. As a matter of fact, he starts from the emergence of certain images to our memory, which then form successions and thus this is *thought, when a certain image recurs in many of these successions, then it becomes an ordering element*, since it links successions which would otherwise not be linked: and this is a *concept* (Einstein 1949).
After all, even in his major scientific works, especially in (Einstein 1905 and 1916) his reasoning, we could say, *crystallizes problems into images until a solution emerges* (Miller 1984). And indeed

we would seem to be able to conclude that Einstein *had the habit to think through images* (Holton 1981).
Very often, finally, the image he uses *to look for words before being able to express thoughts* (Einstein at Kyoto Conference in 1922, cited in: Pais 1982) becomes almost naturally a real experiment, though carried out mentally.
Exemplar use (popular or autobiographical papers):

- the *marble table* and the *shellfish of reference* with which he visualizes respectively the space-time continuum and a non-rigid system of reference upon it (Einstein, Infeld 1938);
- the *rotating discs* and the *flat beings endowed with flat instruments* which he uses to highlight the difficulties and limitations of Euclidean geometry (Einstein 1917; Einstein, Infeld 1938);
- the *two-dimensional ghosts*, as the images the characters in a movie projected on the screen, which have the same incapacity of imagining a third dimension as we have in visualizing a fourth dimension (Einstein, Infeld 1938);
- *men who only know a very small part of the terrestrial surface* and who do not even manage to see the stars (Einstein 1949).

2.3. Thought experiments

Thought experiment is a particular case of imagistic reasoning, in which a real "internal" mental simulation is effectuated through imagination, by recurring to explicit images. The importance of a mental experiment stands out as soon as we consider the common case in which a real experiment would be non-realizable, due to technical reasons or even to the violation of physical limitations. More simply, a mental experiment can also serve to *deducting the impediments* (Galilei) of an experiment which is actually carried out in a laboratory, in order to show the outcomes of an ideal situation, in which the phenomenon at the focus of interest of the scientist is the only one at stake, and it is "pure", as *ceteris paribus* clause is perfectly respected.[vi]
Thus the mental experiment has the same psychological function of a real experiment, though it is carried out within a mental model (Johnson-Laird 1983; Gooding 1990; Boniolo 1997; for a review, see Gooding 1994), being able to produce new knowledge in scientific discovery.
Many are the mental experiment conceived, and we could say literally *carried out* by Einstein. We have here the opportunity to give only a brief list of the most relevant ones.

Exemplar uses:

- the *imagery physical experiments*, it's an Einstein expression, of *the railway coach*: an observer stays in a railway coach in a uniform rectilinear motion along a railway, while another one stays motionless on the platform of a station (Einstein 1905 and 1917);
- *two fluid masses* (a sphere and an ellipsoid) hovering freely in space (Einstein 1916);
- the *happiest thought of my life*: for an observer freely falling from the roof of a house there is no gravitational field – at least in the immediate vicinity (cit. in: Pais 1982);
- the *man in the lift* in two different experimental setting, freely falling and raised with constant acceleration (Einstein, Infeld 1938);
- *to ride a light ray*, the mental experiment which Einstein himself reports to have carried out at the age of sixteen (Einstein 1949).

2.4. Analysis of a limit case

There is, finally, a particular case of mental experiment in which an experiment, sometimes just a calculation, is carried out, under very special, if not exceptional conditions. Similar conditions are realized through an extrapolation to the limit, of the values of some critical parameters. The results

obtained under these limit conditions are then considered in returning to normal conditions and used, for example, to factorize a complex problem into simpler smaller problems or to highlight critical parameters of some physical domain.
Einstein often recurs to the use of an *analysis of limit cases*, and this becomes particularly evident in those moments when he achieves the highest detachment from the traditional thought.
Exemplar use:

- While deducting of Newtonian theory of gravitation as a first approximation to his General Theory in the limit case of a weak and quasi-static field, he calculates in the first instance the value of the constant which is present in the most general equations that bear its name, and, as a direct consequence, the three fundamental observational forecasts of the new theory (Einstein 1916).

3. HEURISTIC SCHEDULING

Wed need two more ingredients for a first sketch of our socio-cognitive model.
The first one is supplied by an intuition by van Fraassen (1987): new theory is constructed under pressure of new phenomena in two logical if not chronological steps. First, *widening* the existing theoretical framework by constructing enough reach models as to allow the possibility of those newly envisaged phenomena, and then *narrowing* it to exclude a large class of admitted possibilities. I call *diastole* the first phase and *systole* the second, and I just need to add a preliminary phase, as *personal diagnosis* on available scientific *ideas*.
The second ingredient is a distinction between personal beliefs and scientific ideas, coming from Hume.[vii]

3.1. Personal beliefs behind heuristics and scientific ideas

I will now try to show some beliefs lying behind discovery heuristics, that Einstein used to manage available scientific ideas and to build new ones.
Let's start with *inner perfection*. As we saw before, the compactness and rigidity of theory links up with nature's simplicity, due to a nature order: *Subtle is the Lord, but malicious He is not* (cit. in: Jammer 1999). We can also state it as the identity of *ordo idearum* and *ordo rerum* of Spinoza, a philosopher dear to Einstein. From here, it derives that what is more general, more widely valid, it is also more scientific: so, scientific progress passes through unification of domains.
Behind *explain-or-assume* heuristic we can easily see the belief in one principle ruling a regular connection: *God does not play dice* (letter to Born, 1926 December 4th, cit. in: Jammer 1999), i.e. everything has a cause.
Also behind *correspondence principle* we find a similar belief, that I express with the clause, dear to Newton, that our theories are as *dwarfs resting on giant's shoulders*. That is the only reason for keeping old good theories as a reliable starting point for any new one.
And what about *covariance/invariance*? Truly, the question is not easy. I suggest to take four beliefs behind this heuristic: (a) there are *no absolute* object and concept (at least as a heuristic principle, of course); (b) this belief is connected with the other belief that all the observers are (or have to be considered as) *equivalent* before Truth; (c) as per Hume, another philosopher dear to Einstein, science is based on *experience* and experience is intimately relative; (d) anyway, behind many *appearances*, Truth is just but one.
If this analysis is pretty correct, we have to add an observation. Patently, all these *beliefs* are assumed without sufficient prove and, perhaps, *cannot* be proved at all. Take for example what Einstein confesses in 1954 (letter cited in: Pais 1982), just before his death: *I was, for reasons of a general order, strongly convinced that absolute motion does not exist, and my sole problem was how to reconcile all this with what we knew about electrodynamics*. Following Hume (1739) one more time, it seems Einstein *having* such claim as a *passive and involuntary belief* before reasoning, for intimate reasons, and not *making* it after a logical demonstration.
Beliefs (in this technical meaning) are implicit presuppositions, tacit premises used as a starting point or guiding principle in reasoning, naive theories and models both tacit or partly explicit, exemplars, prototypes, analogies, images, epistemic routines, relevance criteria, schemata, scripts

and the like (as in Ryle's *knowing-how*, Polanyi's *tacit knowledge* or Kuhn's *disciplinary matrix*). They come from some shared human experience (often in the so called *cultural traditions*), more or less unconsciously, and propagate by *contagion* through education and from mind to mind as a *meme* (Dawkins 1976). So it is better for us to conceive scientist as *living in* them, than as *choosing* them through *acceptation*, as it is shown by (Cohen 1992). Sometimes, beliefs may enter in cognitive dissonance (Festinger 1957) among them or with other better-established ideas. Two events can then happen: some belief becomes object of attention, i.e. a new idea sprouts, or some idea is changed.

On the opposite, *ideas* are more explicit and voluntary thoughts (like Ryle's *knowing-that* under Polanyi's *focal attention*), also if they can be highly irrational. Such ideas are thoughts (about world, self, other people or knowledge itself) that we can discuss, accept, share, state, work out, clarify, contest, as in (Hacking 1999). They can be explicit theories and models, propositional arguments, learned algorithms, clearly stated definitions and taxonomies, etc. However, scientific theory in the so-called *received view* (Suppe 1972) is made by ideas. Coming directly from a more or less conscious and voluntary choice, they join other ideas and beliefs in theoretical networks of different solidity. However, scientific ideas are grounded on and always tied to some cultural belief.[viii]

In conclusion, our model will now count on three building blocks: cultural beliefs behind heuristics, current scientific ideas of disciplinary physics and some "new comer" ideas brought by Einstein from other scientific sources.

3.2. A socio-cognitive model for Einstein's discovery

We will now see how Einstein's discovery can be modeled in a sketched cognitive pattern using three phases.

PHASE 1: personal diagnosis

Scientist activates *inner perfection* heuristic in order to test the existing theory and its tacit beliefs against his own beliefs, more or less tacitly assumed behind all orientation heuristics. In so doing, he diagnoses defects and deficiencies, setting a problem of adaptation for available theory and a pattern for a introducing a mutation in it.

Firstly we can summarize some standard and newcomer ideas in the following sub-phase:

SUB-PHASE 1-a: ***stating theory resources***

1) Standard ideas (and assumptions)
- Galileo's relativity
- Newton's mechanics
- Maxwell's electromagnetism
- Lorentz's electron theory

2) Newcomer ideas:
- Mach's definition of mass
- Riemann's geometry
- Levi-Civita's differential calculus

Secondly, we can remind those beliefs we found behind heuristics in a sub-phase:

SUB-PHASE 1-b: ***activating heuristic resources***

1. Inner perfection:
- nature has a logical order
- identity of *ordo idearum* and *ordo rerum*
- what is more scientific is more generally valid

2. Explain-or-assume:
- there is a principle behind each regular connection

3. Correspondence principle:
- our theories rest on giant's shoulders

4. Covariance/invariance:
- no absolute object & concept
- experience is science basis and it is relative
- all the observers are equivalent
- many appearances, one truth

Then, a confrontation takes place, aiming at removing *cognitive dissonance* between beliefs hold in mind by scientist and ideas, both current and added, together with beliefs tied to them.

PHASE 2: diastole

Scientist stresses the theory along the mutation pattern, perturbing hypotheses usually assumed (both explicitly and tacitly) inside its models (initial conditions, auxiliary hypotheses, *ceteris paribus* clause) in order to let hidden deficiencies stand out. This diversity creation goes along three distinguishable sub-phases:
(a) scientist adds relevance criteria and accents to both new and already available empirical and theoretical evidences, using *orientation heuristics*;
(b) he then stresses theory using *abstraction and orientation heuristics*, while drawing cognitive resources from available beliefs (exemplars, prototypes, analogies, images, etc.). In so doing, scientist perturbs conditions usually assumed inside standard models;
(c) lastly, he assumes new hypotheses as new principles, according to *explain-or-assume* heuristic.

SUB-PHASE 2-a: ***adding relevances***

1. Empirical evidence
- no Earth motion relatively to light medium;
- constancy of light velocity;
- equivalence of inertial and gravitational masses;

2. Theoretical evidence
- Lorentz's invariance of Maxwell's equations;
- Maxwellian field theory as analogy;
- Gaussian theory as analogy.

SUB-PHASE 2-b: ***stressing theory***

1. *Initial conditions*
- free falling observer → equivalence between gravitation and acceleration;

2. *Auxiliary hypotheses*
- simultaneity measurement → time relativity;
- vector parallel transportation → covariant differentiation;

3. *Ceteris paribus clause*
- gravitation free trajectory → link between geometry and gravitation.

SUB-PHASE 2-c: *assuming principles*

Special relativity
- light principle;
- special relativity principle;

General relativity
- equivalence principle;
- general relativity principle;

PHASE 3: systole

Scientist uses *orientation heuristics* and *classical (deductive) logic* under a general *satisficing heuristic*, to reduce the variety of possible theories (*fixing constraints* both theoretical and empirical, and *confronting predictions*) and also to give exact *meanings* to each theoretical term. This selective phase is more deterministic and logically driven than the former two. The emerging theory may be so deeply reshaped, as a seeming revolution and it ideally ends with a *satisficing* cognitive trade-off (due to computation and time limitations against scientist own beliefs).

3.3. Conclusion

The model (see figure), of course, is far to be completed. Still other beliefs and ideas are to be found, and other steps are to be isolated, too. We can also foresee a repeated activation of all three phases, as for subroutines with feedback control, until a final *satisficing* stop is given. Anyway, the plan of the final model is rather clear.

REFERENCES

Achinstein, P., 1968, *Concepts of Science. A Philosophical Analysis*, Johns Hopkins, Baltimore (Mar.).

Boniolo, G., 1997, On a unified theory of models and thought experiments in natural sciences, *International Studies in the Philosophy of Science* 11, pp 121-142.

Cerroni, A., 1999, *Categorie e relatività. Cognizione, metodo e cultura nella scoperta di Albert Einstein* (Categories and Relativity. Cognition, Method and Culture in Albert Einstein's discovery), Unicopli, Milano.

Cerroni, A., 2000, Covariance/invariance: a cognitive heuristic in Einstein's Relativity Theory formation, *Foundations of Science* 5 (2):209-224.

Cerroni, A., 2001, *Beliefs and ideas: socio-cognitive relativity beyond relativism, Scipolicy* 1 (2), www.scipolicy.net

Cohen, J., 1992, *Belief & Acceptance*, Oxford University, Oxford.

Dawkins, R., 1976, *The Selfish Gene*, Oxford University, Oxford.

Dennett, D., 1978, *Brainstorms. Philosophical Essays on Mind and Psychology*, Bradford Books, New York.

Dewey, J.,1933, *How we Think*, Heat, Boston.

Donovan, A., Laudan, L., Laudan, R., eds., 1988, *Scrutinizing Science*, Kluwer, Dordrecht.

Duhem, P., 1906, *La Théorie Physique: Son Objet, Sa Structure*, Rivière, Paris,

Einstein, A., 1905, Zur Elektrodynamik bewegter Körper, *Annalen der Physik* 17:891-921.

Einstein, A., 1911, Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes*, Annalen der Physik* 35:898-908.

Einstein, A., 1916, Die Grundlage der allgemeinen Relativitätstheorie*, Annalen der Physik* 49:769-822.

Einstein, A., 1917, *Über die spezielle und allgemeine Relativitätstheorie (gemeinverständlich)*, Vieweg, Braunschweig.

Einstein, A., 1921, *Vier Vorlesungen über Relativitätstheorie, gehalten in Mai, 1921, an der Universität Princeton*, Vieweg, Braunschweig 1922.

Einstein, A., 1933, Origins of the general theory of relativity, Lecture on the George A.Gibson Foundation in the University of Glasgow, June 20th, in: *Mein Weltbild*, C.Seelig, ed., Zurich.

Einstein, A., 1936, Physik un Realität, *Franklin Institute Journal* 221: 313-347.

Einstein, A., 1939, Science and religion, *Nature* 146:605-607.

Einstein, A., 1948, Time, space, and gravitation, in: *Out of My Later Years*, Philosophical Library, New York 1950.

Einstein, A., 1949, Autobiographisches, in: *Albert Einstein: Philosopher-Scientist*, P.A.Schilpp, ed., Library of Living Philosophers, Evanston.

Einstein, A., Infeld L., 1938, *The Evolution of Physics. The Growth of Ideas from Early Concepts to Relativity and Quanta*, Simon & Schuster, New York.

Fadner, W.L., 1985, Theoretical support for the generalized correspondence principle, *American Journal of Physics*

53:829-838.
Festinger, L., 1954, *A Theory of Cognitive Dissonance*, Row-Peterson, Evanstone.
Finke, R.A., Ward Th.B., Smith S.M., 1992, *Creative Cognition. Theory, Research, and Applications*, MIT, Cambridge (Mass.).
Fleck, L., 1935, *Enstehung und Entwicklung einer wissenschaftlichen Tatsache*, Suhrkamp, Frankfurt
Friedman, M., 1983, *Foundations of Space-Time Theories. Relativistic Physics and Philosophy of Science*, Princeton University, Princeton.
Gentner, D., 1989, The mechanism of analogical learning, in: *Similarity and Analogical Reasoning*, S.Vosniadou, A.Ortony, eds., Cambridge University, Cambridge.
Gooding, D., 1990, *Experiment and the Making of Meaning. Human Agency in Scientific Observation and Experiment*, Kluwer, Dordrecht .
Gooding, D., 1994, Imagery science, *British Journal for the Philosophy of Science* 45, pp 1029-1045.
Hacking, I., 1999, *The Social Construction of What?*, Harvard University, Cambridge (Mass.).
Hadamard, J. 1945, *The Psychology of Invention in the Mathematical Field*, Princeton University, Princeton.
Hesse, M., 1966, *Models and Analogies in Science*, Notre Dame University, Notre Dame (Ind.).
Holton, G., 1981, Einstein's Search for the "Weltbild", *Proceedings of the American Philosophical Society* 125 (1):1-15.
Holyoak, K.J., Thagard, P., 1995, *Mental Leaps. Analogy in Creative Thought*, MIT, Cambridge (Mass.).
Hume D., 1739, *A Treatise of Human Nature*, London.
Jammer, M., 1999, *Einstein and Religion*, Princeton University, Princeton.
Johnson-Laird, Ph., 1983, *Mental Models. Towards a Cognitive Science of Language, Inference and Consciousness*, Cambridge University, Cambridge.
Kosslyne, S.M., 1983, *Ghosts in the Mind's Machine. Creating and Using Images in the Brain*, Norton, New York.
Krajewsky, W., 1977, *Correspondence Principle and Growth of Science*, Reidel, Dordrecht.
Kuhn, T., 1977, *The Essential Tension*, The University of Chicago, Chicago.
Landau, L.D. and Lifšits, E.M., 1973, *Teorija polja*, Fizmatghiz, Moskva.
Langley, P., Simon, H.A., Bradshaw, G.L., and Zytkow, J.M., 1987, *Scientific Discovery. Computational Explorations of the Creative Processes*, MIT, Cambridge (Mass.).
Mach, E., 1905, *Erkenntnis und Irrtum. Skizzen zur Psychologie der Forschung*, Leipzig.
Mamchur, E., 1987, The heuristic role of aesthetics in science, *International Studies in the Philosophy of Science* 1 (2):209-222.
McAllister, J.W., 1996, *Beauty and Revolution in Science*, Cornell University, Ithaca (N.Y.).
Miller, A.I., 1984, *Imagery in Scientific Thought: Creating 20-th Century Physics*, Birkhäuser, Boston.
Miller, A.I., 1998, *Albert Einstein's Special Theory of Relativity. Emergence (1905) and Early Interpretation (1905-1911)*, Springer, New York, 2nd edition.
Misner, Ch.W., Thorne, K.R., and Wheeler, J.A., 1973, *Gravitation*, Freeman, S.Francisco.
Nersessian, N., 1992, How do scientists think? Capturing the dynamics of conceptual change in science, in: Giere R., ed., *Cognitive Models of Science*, *Minnesota Studies in the Philosophy of Science* XV, Minnesota University, Minneapolis.
Ortega y Gasset, J., 1939, Ideas y creencias, in: *Obras Completas* 5, Revista de Occidente, Madrid 1946-1983.
Pais, A., 1982, *'Subtle Is the Lord…' The Science and the Life of Albert Einstein*, Oxford University, Oxford.
Petroni, A M., 1990, *I modelli, l'invenzione e la scoperta. Saggio su Keplero, la rivoluzione copernicana e la 'new philosophy of science'*, Franco Angeli, Milano.
Polanyi, M., 1958, *Personal Knowledge. Towards a Post-Critical Philosophy*, Routledge & Kegan Paul, London.
Popper, K.R., 1982, *Postscript to the Logic of Scientific Discovery,* W.Bartley III, ed., Hutchinson, London.
Post, H.R., 1971, Correspondence, invariance and heuristics: in praise of conservative induction, *Studies in History and Philosophy of Science* 2:213-255.
Radder, H., 1991, Heuristics and the generalized correspondence principle, *British Journal for the Philosophy of Science* 42:195-226.
Reichenbach, H., 1920, *Relativitätstheorie und Erkenntnis apriori*, Springer, Berlin.
Reichenbach, H., 1927, *Von Kopernikus bis Einstein. Der Wandel unseres Weltbildes*, Ullstein, Berlin.
Reichenbach, H., 1928, *Philosophie der Raum-Zeit-Lehre*, Walter de Gruyter, Berlin-Leipzig.
Simon, H.A., 1977, *Models of Discovery and Other Topics in the Methods of Science*, Reidel, Boston.
Suppe, F., 1972, What's wrong with the received view on the structure of scientific theories?, *Philosophy of Science* 39:1-19.
Thagard, P., 1992, *Conceptual Revolutions*, Princeton University, Princeton.
Toraldo di Francia, G., 1981, *L'indagine del mondo fisico*, Einaudi, Torino.
van Fraassen, B., 1987, The semantic approach to scientific theories, in: *The Process of Science*, N.Nersessian, ed., Martinus Nijhoff, Dordrecht.
van Fraassen, B., 1989, *Laws and Symmetry*, Oxford University, Oxford.
Weinberg, S., 1987, Towards the final laws of physics, in: S.Weinberg, R.P.Feynman, *Elementary Particles and the Laws of Physics*, Cambridge University, Cambridge.
Weinberg, S., 1972, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, Wiley, New York.
Wertheimer, M., 1959, *Productive Thinking*, Harper, New York.
Zahar, E.G., 1973, Why did Einstein's programme supersede Lorentz's one?, *British Journal for the Philosophy of Science* 24.
Zahar, E.G., 1989, *Einstein's Revolution. A Study in Heuristic*, Open Court, La Salle (Ill.).

i Thagard's *explanatory coherence* (1992) and Weinberg's *beauty* (1987) are good references for this second component.

ii See e.g. letters to Rosenthal-Schneider, October 13th, 1945, and March 24th, 1950, cit. in (Pais 1982, ch.2).

iii Bohr explicitly formulated the principle of correspondence during the early 1920s for the construction of quantum mechanics, and it is interpreted almost as a fundamental heuristic for science by Reichenbach (1920), Popper (1982, vol. 1), Post (1971), Fadner (1985), and, with reference to the Theory of Relativity, by Zahar (1973 and 1989). See also (Toraldo di Francia 1981), Krajewsky (1977) and the critical review in (Radder 1991).

iv Fuller treatment in (Cerroni 2000).

v Analogical reasoning has been studied as a research aid since Mach (1905). Holyoak and Thagard (1995) list eighteen analogies which prove more or less relevant for some important discoveries or inventions: sound/water waves (Crisippo, Vitruvio), earth/magnet (Gilbert), earth/moon (Galilei), earth/ship (Galilei), light/sound (Huygens), planet/bullet (Newton), illumination/electricity (Franklin), breathing/combustion (Lavoisier), heat/water (Carnot), animal and plants competition/growth of human population (Darwin), natural selection/artificial selection (Darwin), electromagnetic forces/mechanics of the continuum (Maxwell), benzene/snake (Kekulé), chromosome/pearl string (Morgan), bacterial mutation/slot machine (Luria), mind/computer (Turing), gas molecules/snooker balls (historically very common) and atom/solar system (Rutheford, Bohr).

vi Thought experiment, too, has been systematically studied since Mach (1905).

vii A tradition about beliefs-ideas dichotomy can be traced along Dewey (1933), Fleck (1935), Ortega y Gasset (1939), Polanyi (1958), Dennett (1978), Cohen (1992). For some more details see also (Cerroni 2001).

viii Relativism is not a forced way, as it is shown in (Cerroni 1999 and 2001).