A longitudinal approach to the appropriation of Science Ideas: an emerging Cognitive Model

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Paolo Guidoni, Physical Sciences Dept, University of Naples "Federico II", Italy, guidoni@na.infn.it

Abstract: A research approach, active since three decades, is sketchy described. Its aim is to clarify, starting from the phenomenology of explaining-understanding interactions followed along years within groups of students, two mutually correlated theoretical and practical nodes: i) how to restructure the *discipline presentation* (e.g. basic physics and math) to be *longitudinally resonant* with students' gradual *appropriation*, in both understanding and motivation; ii) how to infer a cognitive model able to account for success (insuccess) in the school *active mediation*, but also to validate planning and support strategies invariant across age spans and different content areas. A first approach to basic mechanics, able to coherently and successfully evolve to higher formal levels, will exemplify model activation at school.

Introduction: this paper

This presentation aims to offer a brief survey of a research line which since about thirty years has evolved along two parallel, strictly correlated strands: a cognitive modeling *able to account* for what actually happens (does not happen, we would like to happen) in science and mathematics classrooms, since kindergarten to beginning of university; and an effective and efficient restructuration of both discipline concepts and teaching practices *able to resonate*, in understanding and motivation, with the astonishing potentialities humans exhibit at the beginning of their cultural life (and then appear to gradually "loose"). The results of both strands, substantially unpublished apart from occasional excerpts, are now being systematically organized according to their "reciprocally mirroring" features. Here a few aspects of the research method and of the inferred cognitive model will be first outlined; then a flash-example will be given about the approach to the long term cognitive path that allows for a longitudinally resonant appropriation of basic mechanics. As a conclusion, some hints from neurocognitive research will be recognized as resonant ones with the interpretations and with the suggestions stemming from this independent approach to thought facts.

It is obvious that such a complex and multilateral research line, active for such a long time, is deeply involved and indebted with a great variety of theoretical views and research results (say, from presocratic philosophers to current cognitivist and/or curricular proposals). However, a regrettable choice is a forced one: to prevent this paper body to be almost totally taken by quotations and references, substantially no reference will be given here - even when some Names will (necessarily) appear. The choice will be remedied for in more expanded contexts; experts in the field will anyhow identify implicit acknowledgements diffused in the text.

1) The research: aims, methods, framing assumptions

The research started in the late '70s with an ambitious, yet rather undeterminate perspective: to radically confront with the diffused failure of the scientific-mathematic education by directly and deeply inter-acting with "normal" students in "normal" schools (since the 3 yrs of kindergarten up to university level), and with their "normal" teachers; this, for long time enough to elicit the dynamic features underlying the widespread lack of personal understanding and motivation, both necessary to successful *appropriation* of basic scientific culture.

The goal was then, since the beginning and along the years, one of exploring on one side the implicit cognitive potentialities girls and boys bring to school; on another side - but at the same time – one of trying out the deep rearrangements discipline structures can/must undergo in order to gradually and successfully fit, as through a resonance dynamics, with the students' potentialities themselves; finally, to check across time (up to 5 years, in some cases, with the same students) which long term interaction strategies between developing cognition and self-modulating scientific culture appear to be mostly effective and efficient to reach a cultural appropriation personally meaningful, socially relevant and open to cooperation ad evolution culture appropriation. At the same time the research methodology was also shaped by matter of fact circumstances: researchers, with long term scientific backgrounds in physics, biology, mathematics, psychology, were fully immersed in the project and "scientifically" confronting with cognitive and pedagogical issues in literature; Italian Schools allowed for systematic presence of researchers in the classrooms, totally sharing teaching strategies and teaching interactions in investigated (and connected) areas with in-charge teachers; variations of the standard approaches need always to be such to fully guarantee test-students to reach *better* performances in standard controls at the end of learning cycles; a teaching "technique" of setting up the conditions for systematic, meaningful students discussions, then of real-time analyzing them in correlation with written tasks to address the finalized interactions, was first developed in these years, revealing itself as a crucial key to

research evolution; the possibility to "survive" in scientific departments by periodical (and not so frequent) publications about science teaching results and proposals was a big help; … and so on.

Confronting with unsatisfactory field checks of so many action/interpretation features peculiar to available learning theories (Piaget, Bruner, Vygotskij … et al, to start with), the research went on by slow accumulation and organization of varieties of phenomenological evidence, always mirroring into hypothetical modeling features. And the envisaged model always had to satisfactorily account for the short-intermediate-long term observed cognitive dynamics: addressed as they were by *strategically active adult intervention and support*, but fully involving the understanding-learning subject in all his/her personal characters.

Several basic aspects of such a phenomenology-based cognitive modeling were quickly interfering/merging with the basic framing assumptions which in some sense had a-priori inspired research methods and goals: since some point, a selected set of assumptions-confirmed-by-results was therefore able to act as an (evolving) framework within which to articulate the research strategies, together with their continuous confrontation with classroom data and worldwide hints/results. Here it is just possible to (almost randomly) sketch a few of such *model-framing criteria*, all gradually confirmed by direct evidence and as such implicated in the actual form of the model itself. In "apodictic" format, a satisfactory cognitive model should then:

- exhibit *interpretive* (in observed contexts), *predictive* (in new contexts) *and* effective *interaction-driving* features all along the evolution of life-and-school experience of students;
- account for varieties and complexities in the knowing *subjects*, in the known *objects*, in the cognitive *fits* correlating such poles via the proposed *cultural interfaces* – without systematically removing variety and complexity into "ignorance" and/or "anomaly";
- account, along development times (and since very early ones), both for *different (parallel) levels* of cognitive sophistication always tuned to purpose and context, and for a (correlated) inner dynamical impulse to *cognitive self-expansion* (<all men by their very nature strive to better know>, already according to Aristoteles);
- offer definite help to come out of supervening "problems" (theory-and/or-action centered);
- account for the *basic similarities* (across the wide span of sophistications) connecting students' teachers' and researchers' cognitive strategies, this way promoting and supporting reciprocal empathic "recognition";
- value the fact that thinking is at any level *intrinsically multilateral* (*then* sometimes incoherent, *yet* most of the times globally self consistent), according to a vision quite similar to Wittgenstein's <game of games>;
- accept the *deep constraint* (always a controversial though quite an obvious one) that <the game of games can not be totally formalized> - then explicitely represented (formalizing itself is a game among others!);
- account for the observed *discretization-articulation-correlation of the cognitive games* according to their action/language/purpose features and structures, recognizing and making explicit the founding role of Democritos' realization that <language is the shadow of action> (and viceversa!);
- account for the *substantial continuity in different thought modes* - from perceiving to modeling, from referential to formal ones - all structured around common, basic strategies; in correlation, to account for the observed long term, interlaced *refinement of strategies* themselves from kindergarten to university, and to highlight – in this perspective – effective and efficient *recovery strategies* whenever needed.
- ……
- to make the most of the very fact that *natural experience, natural language, natural thinking, natural strategies, natural knowing* … sit down at the roots of all kinds of thought differentiations, developments and sophistications: even more important, that they shape also the crucial patterns of metacognitive and cognition validating dynamics.

(There are several reasons to make such *reasonable framing criteria* of a proposed modeling as much explicit as possible: last but not least, the role they do have in making acceptable and exploitable by "normal" teachers a proposed theory of thinking, so often repelling them in its technically schematic features).

2) The "cognitive resonance" model: general features

Without following the indented evolution of model core and surface features, without attempting to argue about their reciprocal consistency and support, and without pursuing any completeness, it will now be schematically outlined some model peculiar character. It is worth to remark again that the model itself, in its endeavour to mirror thought dynamics, is *not* looking for a hierarchic (quasi-deductive) construction: rather, its descriptions of thinking substantially acknowledge for a rich variety of *potentially correlated and potentially structured available modes*, which always get their specific form(at)s according to activation-and-purpose modalities. (See below for a physics-based analogy). Model characters, therefore, do not respond to rigid reciprocal roles, but are in some sense all-always co-determining, with variable reciprocal weights, thinking dynamics.

Cognitive thinking is deeply rooted into a few, crucial, dynamical "facts": quite evident as such across emergent cognitive behaviours, quite hard to be sharply disentangled at "local" levels (individual, contextual, temporal, cultural, evolutive … ones). Let's go through.

2.1) At the basis of any kind of *conceptual thinking* (so to say) stands the huge, sophisticated, substantially "black-box" construction of the *perceptual (sensory-motor) thinking:* in all its hardware vs software, syntactic vs. semantic , functional vs. structural … dynamical features. We know not so much of such a system (by the way correlating humans' to animals' cognitive behaviours): however all we know and all we observe confirms on one side the observed *continuity and reciprocal embedment between conceptual and perceptual "worlds"*; on another, crucial, side the reasonable hypothesis of a *syntactic and semantical parasiting by conceptual cognition of the perceptual structure itself.*

2.2) In a first approximation, continuity and embedment can be resolved into some main aspects: i) conceptual and perceptual thinking, as much as they are phenomenologically distinguishable, do exert a continuous influence each one on the other, their interaction-interference (normally a very constructive one) being only in part explicitely controlled at the <game of games> level; ii) there is a *direct continuity* between the two thinking modalities: in particular *referential thinking*, articulated as it is into *permanent objects/systems/states* (and so on) and *permanent phenomena/properties/transformations* (and so on), can exploit its potentialities of "evolutive advantage" only if the two modalities are reciprocally tuned (actually, continuously re-tuning each one vs. the other); iii) sensation has the severe limitation that *correlations among variations* are not directly observable, as crucial as they are to biological success: a move forward, already present in very "simple" animal structures, is then a "purposeful mix" of sensation, pattern construction/recognition and memory which allows the perceptual cognition of "complex" animals (and of humans) to perform directly (let's say implicitely) in quite sophisticated ways; iv) the typically human (crucial) move, commonly quoted as "abstraction", appears then in its core features as one of literally *objectifying correlations* themselves: i.e. one of cognitively handle and hierarchize them according to a *systematic and coherent metaphoric strategy*, that projects the external-correlations world onto the powerful perceptual-cognitive structure already tuned to handle external objects, phenomena and so on: the enormous "evolutive advantage" being then one of transferring the exploitation of correlations (interpreting, planning, considering alternatives, producing hypotheses, and so) onto the functionally, structurally and strategically well dominated plane of perceptually-driven world interactions; v) once any new level of abstraction is subsumed this way into the already available cognitive machinery it starts experiencing, in turn, strong "metaphoric advances" by the powerful expansive dynamics which is responsible (at evolutive as well as developmental level) for the bological pressure to optimize performance: such an intrinsecally constructive mechanism (sometimes labeled as a "bootstrap" one) making, on the other hand, practically impossible (unproductive) any attempt to rigidly classify and rigidly handle different "forms of thinking"; vi) in particular, the metaphoric mode of thinking allows for the onset of an *explicit, again quasi-objectual, metacognition*: always working somehow "counter-stream" in respect to the "logical" constraints embedded in cognitive dynamics, and emerging to awareness in the format of recognized "impossibilities": from non contradiction, to impossible total formalization of the game of games, to incompatibilities in checking completeness and coherence, and so on; all stressing the unavoidably self referential character of the global dynamics; vii) again in particular, the metaphoric (abstract) thinking mode can be recognized as internally structured according to some crucial features already evident in the perceptual one: for instance, elementary "prototypes" of various level are gradually correlated (in evolution as in development) to each other according to flexible structures, accounting this way in a *maximally economic* way (as pointed out by Mach) for the overwhelming variety of contexts; for instance, the intrinsic structuration according to "fields", "subfields", "general fields" … and so on in particular knowledge reflect (sometimes even quite clearly) the original metaphorizing phenomenologies; and so on.

2.3) The evidence for such characters of basic cognitive dynamics gradually and coherently emerges from direct, careful, long-time, different individuals' observation in different contexts. (It is a peculiar feature of all levels of animal perception the "primitive" relevance which is given to the cognitive articulation of any "change" into the meta-categories of variance vs. invariance: so that the very fact that cognitive invariants subjectively emerge as "research results" across the long times and variegated contexts is just coherent with the basic "universal" features claimed by the cognitive model itself). On the other side a cognitive dynamics like the one which has been just outlined would easily result in quite unstable, explosively differentiated cognitive systems (and systems of systems). Actually, what works (also) as a stabilizing cognitive subsystem, able *to keep at reciprocal convergence growth, use and structuration* within and between individuals, at the same time exhibits deep marks stemming from the dynamics itself (this way confirming the basic model assumptions): it is now urgent to qualify the *variety of cognitive roles assumed by language – as well as by generally "symbolic" processes*. Let's see some of them. i) Various symbolic (or "pre-symbolic") forms of thinking-and-behaving, up to "protolanguages", have been documented in animals (and plausibly more could be uncovered): the access to language and symbolism appears then as a natural cognitive potentiality best developed in appropriated "cultural" environments. ii) Though an evolutionary account of human symbolic and linguistic processes (as hard as it is) would be of crucial interest in cognitive modeling, it will not be attempted here. iii) What is by now recognized in human languages as "universal" basic structure(s) of syntax and grammar (Chomsky's perspective) has very evidently to do with a basic structural scansion of external-and-meaningful reality

features, to cognitively reorganize them in purposeful formats. In other words, in the language reality appears as "projected" (forced) into a discretizing categorization which privileges stable object/systems (nouns), their recognizable and variable "properties" (adjectives), their movements and/or transformations (verbs) according to various modalities (adverbs), the space-time-causal links at the roots of recognizable phenomena (syntactical terms and verbal forms) … and so on: it is not difficult to identify across the *structure of grammars and syntaxes* a quasi-isomorphism (a *dynamical resonance*, to be more specific) with the basic structures of *referential cognition* (perceptual and/or conceptual as it is). iii) Language (and symbolization) perform therefore, together with the communication one, a variety of crucial cognitive roles: e.g. on one side they act to stabilize the cognitive dynamics (within and between individuals; most importantly at the level of cultural transmission, where cognitive categories and strategies are implicitely shaping the developing mind by their resonant effectiveness); on the other side it allows for variationality and expansivity of the cognitive dynamics itself, in particular supporting the driving roles of metaphors and hypotheses strategies. iv) In particular, it is clear since the oldest written documentation that sensory-motor metaphors do deeply structure the roots of "abstract" (and "scientific") cognition, besides the ones of "natural" (and "poetic") discourse: so the conclusion of a mathematical proof has to be "seen", as a behavioural guess has to be "sensible" … and so on. v) Still in particular, it is probably by the mediation of language metaphoric power that the basic "logical" metaphor stemming *from* space images of two dimensional sets has taken its roots and relevance, as it is until now documented by the space-time-movement words which characterize elementary logics in all languages. vi) And so on.

2.4) The tortuous paths of the metaphorization processes, eventually leading to handle *aspects* of the complex world of correlations as quasi-isomorphic to *parts* of the (also very complex) objectual and phenomenic world, become more evident by a parallel study of the (variously) abstract components of our language, and of their intriguing *appropriation* by cognitively developing young people. There is no room here to go across an analysis of this kind of processes, where the strong a-priori constraints of *given* "relevant" world characters, together with *given* "correspondingly appropriate" language and behaviour modes, powerfully act on cognitively natural pre-dispositions: to eventually enforce the *internal resonance habit* characterizing our ways to think, ways to act, ways to speak … <ways to live>, in Wittgenstein's words. Just three typical examples, as banal as they may appear, to address the attention to this problem (a crucial one to understand cognitive development within cultural pressure). i) <*Length*> is an "abstract noun" which our grammar hands as an "object noun": we say <*the* length (of) …, *this* length, *a great* length … etc>. It is obvious that no "length-object" does exist: rather, length is one of the ways (actually, a prototypical one) by which we can characterize concrete objects (technically, an "attribute", a "variable", …). Why a quasi-object noun, then? A sensible (though complex) answer is indeed possible within the framework of the model. Here, just a crucial remark: in its substantivation the word <length> actually refers to the fact that by selecting a particular way-to-look-at the considered object among the many available ones (*looking-at by* length: rather that by weight, by price, by beauty, by symbolic meaning …) it is indeed possible to realize a *stable, meaningful resonance* between a subjective *cognitive "predisposition"* and an objectual *invariant "property"*. Exactly what happens with the perceptually successful apprehension of a physical object: in both cases the resonance process reinforcing its two referents. And the "objective length" will then become visible, measurable, comparable, structurable, and so on. (ii) <*Force*> is, again, an "abstract noun" which our grammar hands, again, as an "object noun": we say <*the* force, *two* forces, a *great* force, … a force *acting on* … etc>. It is again obvious that no corresponding object exists: rather, this substantivation (again a referential-and-metaphoric one, as it occurs in everyday language) implies the ability to "see" the *invariance of a complex correlation* experienced in a variety of contexts: where the perceptual feeling of a bodily <doing force> is first isolated, then connected to the variety of co-occurrences in the (necessarily) involved external system(s). Again, transferring the concrete doing-force contexts to quasi-objectual cognitive contexts, where any doing-force is materialized and represented as a "something", happens indeed to be a "winning" cognitive strategy: already present in natural thought-language strategies when, quite late in cultural history, it got to be "formalized" (see below for more details). iii) What about <*number*>? Again a cognitive, linguistic, symbolic, formal … quasi-objectual mark to characterize the resonance between a way-to-look-at (i.e. looking by numerosity and nothing else at a delimited group of discrete objects) and an objectual property of a piece of the world. Again, much more than that: the possibility to directly handle an internal construct not only able to resonate in trustable way with a variety of external contexts-conditions, but endowed with the potentiality to become (just by its character of faithful duplication of objectual properties) the cornerstone of a self consistent cognitive world able to successfully superpose its structure onto the objectual one.

2.5) It may be by now clear that this kind of modeling tends to look at cognitive dynamics as one characterized by an internal *"duplication" of features, and correlations among features*: somehow "mirroring", or "simulating", the external ones that cognition itself is able to isolate (to "identify") then to "recognize" as relevant ones, then worth to be *appropriated*. In this always entangled construction-and-use process, the ability of cognition to modulate in a continuous way the "mixing" between perceptual conceptual and metacognitive

dynamics, in referential and metaphoric modalities, plays the central role. And dynamics itself appears to be setup (as much constrained than activated) by a *resonance-searching and resonance sensing, far-deep biological "engine"*: one able to detect and to pursue the *reciprocal adjustment-fit between aspects of external and internal worlds* (internal-to-external, internal-to-internal, external-to-external features …) by the same universal criteria by which a living being is supported and addressed in his good/well vs. evil/harm judgements and behaviours. Radically: the internal feeling driving us (most of the times successfully) to maximize cognitive internal and external resonance(s) in local as in global contexts ("cognitive fitness", so to speak) has the similar roots and sensing apparatus of the feeling which drives us to maximize our overall wellness, to which cognitive fitness is in turn a crucial instrument. And all the by now well acknowledged correlations between cognitive, emotional and values worlds strongly confirm this way to look at cognition itself.

In this perspective it is also evident that the host of "representational" strategies characterizing the modulations of our culture-driven cognitive strategies (from symbolic to linguistic, from iconic to formal ones) are themselves driven by selective (reciprocal) resonance criteria: where the crucial node pivoting the cognitive "duplication" game is localized in its inner (software and hardware, so to speak) schematism-and-partiality features. Only parts (better, projections) of the complexity can in fact be successfully duplicated into meaningful and manageable internal entities: in any case at the price of a schematization, directly stemming from the structures of the "simulating hardware and software" by which duplication itself is setup.

Obviously such a continuous, intrinsically redundant duplication-simulation process is by itself subject to uncoherences: internal ones (emerging when different patterns "should" be reciprocally adjusted to fit external pressure); and external ones (emerging when a pattern internally elaborated according to criteria "other times" successful does not fit any more to a new kind of external evidence). Since the earliest times of metacognitive reflection, "philosophers" have noticed and discussed such an intriguing problem, and proposed ways to come out of it. An extreme one (from Plato and Aristoteles to Leibnitz and Hegel to some contemporary epistemologists) is to postulate some kind of a-priori granted correspondence between "absolute thought" forms and "absolute world" features: the problem being then one of gradually "uncovering" a satisfactory (asymptotically true) match between the two. An alternatively extreme one, which has been first icastically worded by Protagoras (then substantially misinterpreted, then dismissed along the centuries) is the one assumed by this cognitive model, in its intrinsically dynamical characterization: i) *any* "discourse" (*logos*: part-aspect of the cognitive system), due to its origin from contextual-and-metaphoric inferences projected and restructured to fit into a uniform "language" structure, is by its very nature potentially contradicting other parts-aspects of cognition, when developed only according to its internal coherence; ii) to overcome such a quite normal difficulty, the normal success strategy is always one to produce (to invent ex-novo) a "more powerful" (*kretton*) and more complex discourse (mostly, by new metaphoric strategies), featuring the possibility to reframe the emerged contradiction as a particularization of different but not incompatible ways-to-look-at: the ones which by now are coherently inserted and controlled within the new discourse structure; iii) the validity judgement about such a new discourse cannot be pursued looking for criteria ("principles") somehow external to the global cognition (and values, and emotions) system in its present dynamical configuration, but has to be problematically found – time after time – *within* itself (*metron anthropos*, man is the scale for all things, Protagoras was claiming: with associated, multimillennian scandal). Clearly a lot of the evolution of scientific thought can be understood (also) this way; while one might again remind Wittgenstein's claim that we cannot play a game of giving game of games a definite form; or even Godel's claim that to check for completeness *and* coherence of a "formalized" system it is always necessary to activate a "more powerful one" including it.

2.6) The characterization of the model could (should) continue, but it is now time to sketch some of its implications. Before doing it, three other peculiar features will be just evocated by proposing a physical analogy to the model itself. The object-like ("machine"-like) representation of cognitive dynamics (or parts of it), quite rarely coupled to self-critical attitudes, is as old as human documented reflection: from Zuang-Zi (V century B.C.) to Fodor and to neural-networks simulations, the effort to explore thought by assimilating it to peculiar thinking products has proposed an impressive series of quasi-models. (Several times quite "useful" ones indeed to the progress of reflection). The image being proposed here is just one among other "physical/objectual" images (biological images, like the one comparing cognition features to living/evolving organisms and species, are probably the best fitting ones – even if they often appear as complex and badly known as the "thing" they try to reflect). Let's take the way contemporary physics is modeling an aspect of reality identified as a "field" (a "quantum field", in particular). It is a "something" assumed to be physically real (actually the basic physical root of all kinds of observed reality), but impossible to be assimilated to the perceptually based conception of "object". Further, endowed with *strongly correlated characters* of internally structured "content" and externally structured "interactivity" (we can model the field by inferring structure from interactions and/or by predicting interactions through structural features). Now a field features, among others, some interesting "reality" characters in its structure/interaction, easily extended to cognition dynamics: its *reality is actually a potential ("virtual") one*, in the sense that it is manifesting only through the variety of *possible* internal and external interactions summing up its very "nature"; it is a very *redundant one*, as compared to our technical possibility to

exhaustively model the internal elements/relationships "closing" up to account for structure/interaction characters; it is, finally, a *highly hierarchized one, according to quasi invariant modes,* but also subject to strong contextual rearrangements, according to the features time-by-time "evocated" by the meta-constraint that *external inter-actions (with a different field) are driven by reciprocally coherent features*. It is clear that the proposed image (extending to almost all the "technicalities" which qualify a quantum field) can be even more confusing not-physicist people: however it also appears that the thought attitude/tendency/ability to metaphorically reinvest its most sophisticated products into (unavoidably partial) self-modeling is just another confirmation of the proposed cognitive model, and of the self-limitations it coherently accepts.

3) From the model: a longitudinal, resonant approach to disciplines (e.g. phys & math)

The metaphorizing cognitive dynamics, crucial as it is to culture appropriation and exploitation, is indeed a *natural* one – i.e. accessible to all normal humans, up to high degrees of sophistication. It is not, however, a *spontaneous* one, as compared to the complexity of the cultural articulation characterizing our ways of social life, and to the compressed times of individual development. Therefore beyond implicit appropriation of the everyday basic culture under the pressure of everyday full immersion in it, explicit cultural appropriation along the pathways of strategically defined metaphorizations needs to be purposefully addressed and mediated to stimulate and to support cognitive autonomy (in contrast to substantial training/conditioning): and this could/should happen within the school social context in a prototypical way. Averroes was saying that any *individual intellect* needs, to develop, to be <fecundated> by the *general intellect* – culture, in our words – through the mediation of a purposeful, mirroring, empathic ("resonant") interaction with a more developed individual intellect; while the contribution of any (mortal) individual intellect to the evolution of the (immortal) general intellect occurs by a peculiar character of the former one: its attitude to *creative imagination*. The cognitive model being sketched here substantially subscribes Averroes' insight. But this means that schooling has to be planned according to *long-term-evolving cognitive paths* ("conceptual corridors" in Confrey's words): paths which the research has eventually proved to be resonant ones with the ever evolving cognitive potentialities of students, and whose appropriation by teachers makes able to address and support by resonant interactions the "conceptual trajectories" of groups and of individuals. (Notice, by the way, the everlasting power of the "path within landscape" metaphor to account for cognitive growth/evolution, since presocratic philosophers to Ludwig Wittgenstein, and beyond). And just at this point the path of the research here accounted for is merging its two strictly correlated threads: an effective cognitive model to actively foster/induce cognitive resonance; an effective (re)shaping of conceptual paths within disciplines landscapes, to actually meet students' resonance potentialities. Three examples of (still general) *discipline-centered strategic choices implicit in the model* will now be briefly outlined under the heading of *strategic teaching questions*: what about physics vs. mathematics (so to say, factual thinking vs. formal thinking)? what about scientific modeling (a specific "as if" thinking), e.g. in physical contexts? what about the "pre-requirements" always claimed to be necessary to any definite understanding?

3.1) From the point of view of this model, the basic opposition of physical vs. mathematical thinking is well outlined already by Aristoteles (this way anticipating a sound epistemological answer to Wigner's worries about the <unreasonable effectiveness of mathematics …>). According to Aristoteles himself, mathematics and physics as specialized endeavours respond to *two different, basic ways-to-look-at the same world phenomena*: the former aiming to isolate the structural features (at the origin, substantially space-like ones) embedded in *all* observable contexts (in this sense universal, then "abstract" ones), and gradually organizing them as in an autonomous quasi-objectual, this way totally coherent, fictitious "world"; the second striving to schematically-but-faithfully "duplicate" the essential features of classes of phenomena by "fitting" universal structures already in mathematical (logical) formats (whenever and whichever available) with context specific and ad-hoc "formalized" characters, all being structured by "causal" (again metaphorically expressed) links. Obviously what comes out are, in both cases, complex sets of "hardly entangled" structures of metaphoric elements and relationships substantially "simulating" space ones; structures which are culturally handled and represented in quasi-objectual formats, that as such substantially prevent (instead of favouring) directly "intuitive" resonant appropriation. On the basis of neurocognitive evidence Dehaene notices that even basic arithmetic, as it has been culturally structured, *is* cognitively very difficult (basic physics all the same): but an insightful cognitive-and-cultural mediation, acknowledging and making (also metacognitively) transparent the state of facts, actually *can* do the job to gradually drive individual thinking to a resonant appropriation of cultural ways-to-look-at, factual (scientific) and formal (mathematical) ones.

3.2) Let's take the example of physics-peculiar modeling strategies (something quite similar can be said about other scientific areas). At the origin stands the basically perceptual world scansion (see above) into "permanent systems" and "permanent variables", then into *systems interactions and parallel variables relationships and correlations*, then into "permanent phenomena and phenomenologies", eventually exhibiting *causal links* (as space-time metaphorized): all being quite satisfactorily (so to say) mirrored by the *syntax-and-semantics (mainly) constructive interference* featured by natural languages, *and* by (independent)

symbolic/iconic representations. (For instance a cognitively crucial node, impossible to be fully articulated here, is rolled up into the very primitive notion of "form", powerfully linking and entangling to the cognitive treatment of systems the handling of "directly insensible" relationships between variables - this way projected towards "objectual" metaphorization). What physics is doing is just to systematically and coherently exploit such a "natural" approach (and making such a point explicit is a powerful key to successful "teaching" mediation at all ages). Three basic obstacles, however, actually make the cognitive approach to the disciplinary modeling to be felt by many people as quite an obstructed one: i) on one side, <reality itself is not fully separable> (as D'Espagnat notices about quantum physics): systems interactions and variables relationships actually *are* totally interlaced in nature, and quite sophisticated strategies have to be at work (nothing to do with Piagetian prescriptions) to de-interlace (then to re-interlace) them in emblematic contexts; ii) on another side, for "good" (!) cognitive reasons our formalization systems have evolved in quite different ways on the two fronts of interacting systems and "function-like" correlations of variables: this way our physics manuals (as our experts' physical thinking) are now mainly filled up by "computable formulas" correlating variables and parameters variations, while the parallel (crucially underlying) systems interactions are mostly taken in charge by linguistic statements (easily misinterpretable as they are by their seemingly loose, "un-formalized" format); iii) finally, physics modeling is mainly presented within context-adjusted, supposedly emblematic framing conditions: without accepting the burden to explicit the complex cognitive networks that (already in "common" experience/knowledge) correlate and hierarchize our perception-based, action-based, … prototype-based, … generalization based, principles based … cognitive-and-operational behaviours.

3.3) It is a quite widespread commonplace in discussions about schooling problems the accent which is placed on the "pre-requirements" (always on the side of pupils!) supposedly necessary to the success of any "further step" in the teaching-learning interaction itself. There is (obviously) a sound basis to such a worry: the powerful path-metaphor to account for cognitive evolution, already evocated above, being clearly substanciating it. But a metaphor, as partially significant and successful as it may be, is always a partial one: in this case, able to trap theory (remember about Piaget's discretized-and-aligned developmental stages) as well as practice into substantially blind cognitive assumptions. It is *not* this way that cognitive dynamics actually works (conditioning does!). Much more a sound one is indeed the Vygotskij's basic metaphor: "local" cognitive progress in social context being seen as an emersion out of a "possible-proximal-development region", where some element of "new" knowledge has coagulated to explicit and stable appropriation by an active and finalized adult intervention taking into account all the *implicit as well as explicit* "pre-conditions" of the learner. It is clear from what has been said that the model presented here substantially accepts (and develops) such a view. To end up, just three comments. i) Rich, potentially evolving proximal development regions are not for nothing: they have, in turn, to be continuously fostered/enlarged (*also* in their idiosyncratic characters) by responsible and competent "teaching" mediation (quite often, after some years of schooling proximal development areas appear as burn out by their exploitation in explicit instruction, without the renewal the enrichment and the growth which only would allow for further cognitive growth). ii) A "region" is a region (at many many dimensions, in thinking space!) and not a line interval: so, one *can* get out of any definite region by a wealth of *different moves resulting in different "acquisitions"*. In other words: cognition, as a resonance-mediated continuous (continuously evolving) activity, is by itself a *locally highly non-linear process* (icastically typified by the Platonic myth of "recognizing"): and all the attempts to reduce it to quasi linear sequences of state/transformation "unit" steps miserably fail at the matter-of-facts level (remember Gagné's "curricular" proposals). All this might let teachers' task to appear as an almost impossible one (then forcing them to assume regressive, "strictly deterministic" views/actions), without the support of a *cognitive model* and of a *discipline restructuration* taking explicitely into account the long-term cognitive evolution, and its necessity to be insightfully supported: two correlated aspects of a dynamics which *can* be satisfactorily controlled/addressed according to resonant (instead of dissonant) assumptions.

4) An example of "mediated resonance": the approach to "rules" for basic mechanics

Typically, the teaching approach to basic physics stresses two (correlated) "metacognitive" aspects: on one side the serious "dangers" unavoidably connected with messing up physics understanding by any attempt to involve in it bodily experience; on the other side the intrinsically discontinuous relationship separating "common" (misconceiving) cognitive habits from "scientific" (correctly conceptual) ones. And a "philosopher" like Parmenides was just first opening the endless story of doxa (opinion) vs. epìsteme (true knowledge) opposition, dominating western culture up to present times. The general assumptions of this cognitive model are just the opposite ones: to better illustrate them, let us briefly go through to the very first steps of an actually resonant path to appropriate basic mechanics from the beginning of schooling to full formalization.

- One starts by the explicit analysis of static situations: quite naturally occurring references to motion situations are well accepted all along the initial path, but explicitely memorized-and-postponed (actually, they will be later resumed and treated according to a strict, successful extending-analogy to static ones).

- The physically crucial notion of “body” is first assumed in its literal, experience-laden reference: then gradually extended to encompass any physical “system” in its fully material variety of identifications. It is crucially important to learn to “mirror” body features vs. objects ones.
- Isolated “forces” do not exist: the basic notion (physical fact) being the state of “doing force” of a definite system, this way involving at the same time and in correlated ways its internal structures and its external interactions.
- To “do force” by a definite region of its boundary, a system always needs an external, “antagonist” system counter-doing force in the same region: in any of the possible “force-regions” of a given system interacting with others, the different “doing force” are at global equilibrium. If the interaction is just with one system, the two “doing force” can be described as two equal-and-opposite actions – then as two abstract entities <forces>. This way two forces can be seen as equal ones even if originating from totally different systems.
- Any system “doing force” must interact by at least two boundary regions: in abstract format, the sum of all the forces done by any system has to be zero (if the system is interacting in just two regions, the exerted forces are opposite ones).
- The state of doing force always de-forms the system in reference with its “natural equilibrium” state: this is true in various (even very different) ways for both internal structure and external shape and features. As it de-dormed by interaction the system always gains or gives up “energy” (see below) according to modes which are correlated to its doing force.
- “Forces” as abstract entities characterizing systems interactions can be added up to correspond to observed interaction features if all systems are doing force along a common direction (if “forces are parallel ones”). This allows to measure any force action by “equilibrating” it with a number of “unit forces” defined by the reproducible deformation of a standard interacting system.
- (According to the previous rules) forces are “transmitted” across systems: in the case of a “chain” of interacting systems the force done (sensed) by the first system is equal to the force done (sensed) by any other.
- To allow for the functioning of the world, force chains must be closed: this can happen immediately for some systems (think to two hands pulling a spring), but must finally happen in all situations (by the intervention of the, always physical, “reference systems”).
- A measuring instrument is a particular system which, when iserted into a chain of different systems doing-force, transmits the force and at the same time “transduces” its deformation into an easily observed (more or less linear) external change.
- Some systems (as living systems, motors, etc) can be seen as “active” systems: they can be internally controlled in their doing force, this way “constraining” the interacting systems to do force at equal and opposite rates in all interaction regions. Other systems (a spring, a plastic object, a gravity or magnetic field …) can be seen as “reactive” systems: to them, physical configurations (and configuration changes) are univocally correlated to their doing force.
- The relative motion between two systems (eventually, one of them a reference system) is itself a system subjected to the same, above specified, interacting rules: its “natural equilibrium” state just being the “unform motion” state.
- ……
- Energy aspects can be introduced in two ways: i) inferring them from forces phenomenological rules, ii) developing them by a completely independent phenomenological path (in turn allowing to directly infer forces rules): what is crucial to the proposed approach is that *at any level of understandig and representation* the interlacing between “force” and “energy” ways-to-look-at the same physical facts (as their extension to momentum, angular momentum and so on) rests on “formal” (structurally universal) aspects. At any level, “mathematics” clearly appears as embedded in the same reality as “physics” is.
- Iconic and schematic images illustrating this approach, together with an outline of its full formal development including motion phenomena, can be found in the Author’s lectures at the 2003 International School of Physics “Enrico Fermi” (E. F. Redish and M. Vicentini Editors, IOS Press – SIF, 2004).

(An approach to stimulate and to account for cognitive dynamics of students presented basic Thermodynamics at the level of the upper-secondary school, as developed within one of the research projects referring to this cognitive model, is being proposed at this same Conference: see Levrini O. *et al,* A longitudinal approach to the appropriation of Science Ideas: a study on Students’ trajectories in Thermodynamics).

5) As a conclusion: resonant hints from neurocognitive research

Just to conclude, it seems interesting to notice that many cognitive dynamics hints, presented in recent years as results from quite diverse neurocognitive research strands, can in fact be seen as at resonance with the model presented here, which has been (continues to be) developed and validated by completely different (totally “phenomenological”) methods.