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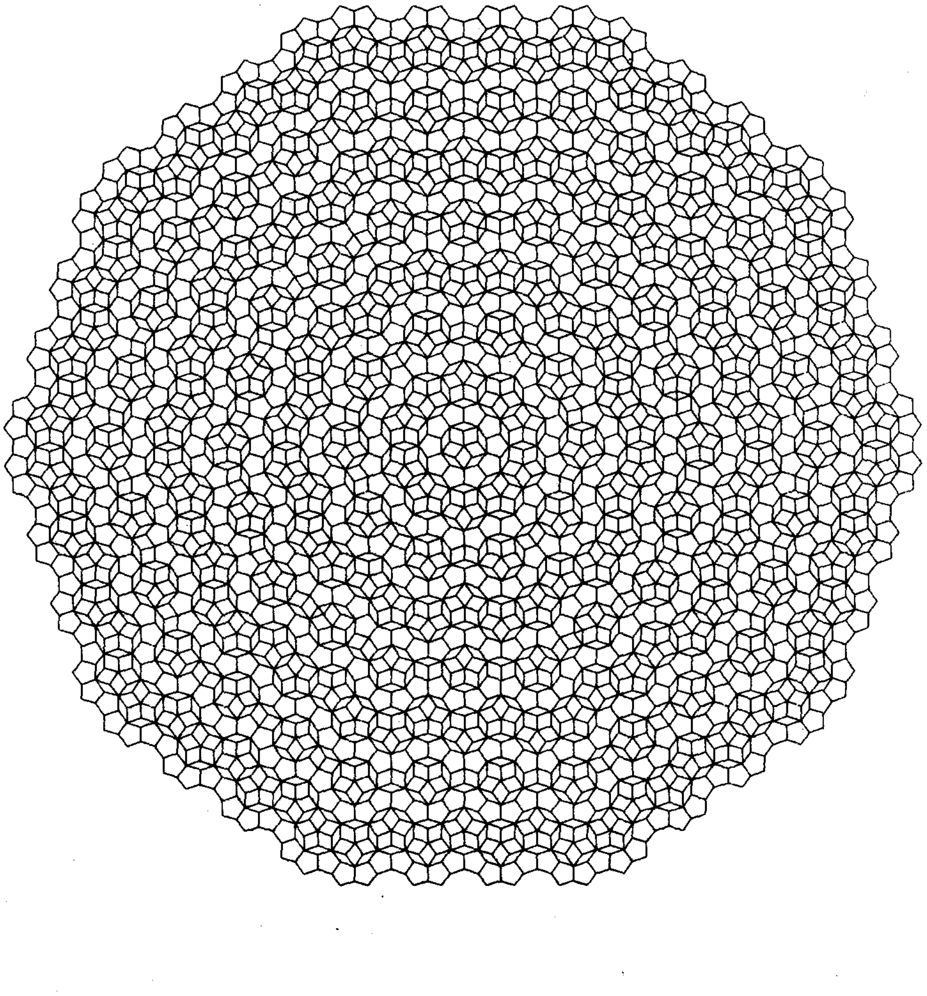

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COSMIC EVOLUTION AND SYMMETRY

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1. INTRODUCTORY

The universe appears to its internal observer as being characterized by three dominant features: the energy flows that mark its inherent internal dynamism, its stratification in largely decoupled energy levels, and the evolutionary nature of its history.

Energy is a mythical notion that is hard to define, but we can study most modalities of its flows and their transformations with reasonable success. The instrument of choice for doing this is provided by the interactions between the material constituents of the observable universe.

There are several types of interactions operating within specific strata of the energetic spectrum. The dominance of some of these interactions relative to others affects the overall character of the observed universe, an effect that can be plotted into periods on the evolutionary scale; for example the era of the dominance of radiant energy, followed by that of matter and more recently by the dominance of information (Chaisson, 1987). Energy then is the ultimate substrate of the material universe, the stuff out of which everything observable is made.

Phenomenologically, interactions are of two distinct types; those that are internal to an energetic stratum, and those that bind different strata together into a cohesive whole. The former are *intralevel*, the latter *interlevel*. They have different characteristics that are of interest in the present context. The former are characterized by certain types of *symmetries* which are absent from those bridging the gap between energetically distinct strata. So it is to be expected that the representations of these different interactions will be radically different, and present different problems.

2. PHILOSOPHICAL PRELIMINARIES

What follows is about key features of scientific discourse and belongs to the tradition of natural philosophy; therefore it is useful to remind ourselves that science is a description of nature as we observe and imagine it to be.

2.1. Invariants and the Laws of Nature

Observation and imagination are both essential ingredients in the scientific enterprise, since our ambition is to encompass the whole of nature in our representation, while our observations, whose role is to validate the claims we make about our representations, are of necessity severely limited by local conditions, by *the here* and *the now*. Indeed, the discrepancy between the scope of imagination, which knows no empirical constraints, and that of observation, which is inherently localized, is such as to call into question the very feasibility of the scientific enterprise. The more so as we have reasons to believe, on grounds of the theory of relativity, that there are whole regions of the universe that are beyond all possible observations.

While it is clear that our knowledge of nature will always be limited and leave us still hungering for more, we have reasons to believe, or at any rate to hope, that much of what we manage to learn is not just a figment of our overactive imagination, but does indeed correspond to what there is. And the most compelling of these reasons is undoubtedly the apprehension of invariance in patterns of observables, the sort of thing we call, with some justification, "laws of nature".

It has been a truism, at least since Herakleitos, that every moment is unique, and ever since Protagoras, that every observation is too. But it has also been a truism, at least ever since the Pythagoreans came up with a respectable method of justification [Heath 1929], that some representations of nature are true "in all possible worlds", that they could not be true. And so we are faced with both the evanescence of discrete observations and the perceived invariance of the patterns they occasionally form. Consequently, the scientific enterprise is naturally focused on the identification of invariants and on their representation in some suitable form or language. An invariant, lest it be deemed "trivial", can then be seen as the symptom of a conservation law or principle, and be expressed as a corresponding symmetry in some parameters in the representation of nature (Greenberger, 1963).

It is not surprising therefore that invariants of various sorts have surfaced in the development of science, and nowhere more clearly than in the study of the material substrate of the whole of nature, in the domain of the so called "fundamental interactions"[1].Therefore, the thesis of this paper will be articulated in terms of these interactions. This is not unduly restrictive in the present context, given that their importance for understanding the evolutionary characteristic of the material universe is truly fundamental, and that the relative clarity of their case is a decided advantage at this level of discourse.

2.2. Remarks on Representation

The hierarchical ontology of the language of science includes the *events*, which are the givens, the patterns they form, which are inferred when the events are observed within the proper perspective, i.e. the *laws of nature*, and the *characteristics* these exhibit (Wigner, 1987). Given the focus on phenomenological invariance, the patterns to be represented in scientific discourse should be independent of the particulars of the case, which are contingently variable. More specifically, they should be independent of initial conditions, though not of their theoretical and experimental contexts, since in order to see a pattern, one has to look for it in the right way, and so observations have to be carefully prepared (Duhem, 1954; Heelan, 1995).

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[1] Cf. However, P. W. Anderson (1972)

To say that language represents something other than itself is to say that it is "symbolic", that it stands in a particular relationship to something else. More specifically, a description encodes a *criterion of identity* for something else. This criterion is the *structure* of what it represents, which is inherently complex. Even in the case of a point, the paradigm of what is simple and can be named, the name standing for it must have a *sense*, i.e. it must be part of the language of description and be linked with other expressions (Frege, 1980). Without these connections, which are constitutive of its sense or *grammar* (Wittgenstein, 1958), a name cannot represent anything. It is only in terms of the relations it bears to other sets of points, for example to coordinates, that a point can be identified in an objective way.

An expression functions as a criterion of identity for what it represents only to the extent that it has something in common with it, namely a *structure*; i.e. it must be isomorphic to what it represents. A descriptive expression therefore is an *analogy* [Steiner 1989],the mechanism of which is the isomorphism just mentioned. This is what is to be understood by "symbolic" in the present context. The language of description, and by extension the language of science, is inherently *structure specific* (Wittgenstein, 1971).

There is much advantage to be derived from having the language display overtly the structures that validate its analogies. This is the primary reason why the language of science, by contradistinction with that of natural history for example, is mathematical. Thus it is that analytical functions provide the syntax needed to bring the global (i.e. context independent) theoretical notions to bear on the inherently local observations in a manner that is representationally perspicuous.

Theoretical notions express the sense that is made of nature; as such they embody the *perspective* within which Nature is to be observed. Being global, that is independent of the contexts of observation, they are inherently *invariant, a sine qua non conditio* for the representation of the laws that govern the unfolding of natural phenomena in all observable contexts. So the notion of a structural criterion of identity applicable to what there is whenever and wherever found, implies its invariance in all contexts of observation: thus the globality of the criterion is reinterpreted as the *universality* of its representations.

Consequently, the *laws of nature* are expressed in terms of observables, as they should, given the necessity of constraining the role of the imagination in the representation of nature to the scope of what is ascertainable. So, to make explicit the claims of invariance, the contexts of observation have to be encoded in the representation of the phenomena themselves, that is, in the phenomenologies. This function is ordinarily discharged by the variables that represent the dimensions of the relevant semantic space, and in principle those of the corresponding observational space as well (Farre, 1995).

Variables, whether semantical or more abstract, are place markers for sets of values to be got in or derived from the observational domains, either directly by measurement, or indirectly by calculation, using these measurements to determine the exact value of the complex expression for a particular context of observation. Variables normally range within stipulated limits or boundaries, and can be made to exhibit other characteristics, such as symmetries, a symmetry being an invariant.

3. EVOLUTION AND THE ROLE OF SYMMETRY

The Experimental Discovery of the *Fundamental Interactions* was achieved in the fifties and sixties, and culminated in the seventies in the so-called "Standard Model". The search for the constitution of matter also revealed that nature is *energetically stratified* (Anderson, 1972; Schweber, 1993). Each stratum is characterized by sets of invariants, and fundamental states are described by fields where interactions are governed by underlying symmetries. These symmetries thus function as criteria of identity for intralevel interactions and serve to taxonomize the strata in which they occur.

The strata are energetically distinct and clearly delineated (e.g. by the inverse relation between the mass of the field particles and their range). Energetic distinctions aside, the stratification of complex particles and particle systems implies causal relations between adjacent strata: the interlevel interactions which are characteristic of the hierarchisation of complex systems. However, these strata are largely decoupled, making the representation of their causal relations particularly difficult (Cao, 1993), a point to which we shall return when discussing interlevel interactions.

The observational evidence for the evolutionary character of the universe itself and for its energetic stratification gives point to the search for the properties of the initial energetic substrate which animates the whole of nature. This quest, which thus far is removed from the possibility of observation, is guided in large part by the likely form of the primeval symmetries that are thought to have been operative at these exceedingly large energies (Ross, 1985; Belokurov, 1991).

3.1. On Symmetry

The discovery of the stratification of interactions has given priority to the study of the principles of invariance and to the role they play in the description of nature. These principles involve analogies of a higher order than those of the laws of nature (Steiner, 1991). They form two main groups, the *classical or geometrical symmetries* based on the coordinate transforms of relativistic 4-space, and the *dynamical or internal symmetries* that are specific to a particular type of interactions. The discovery that the dynamics of particle interactions can be determined by considerations of symmetry has further encouraged the search for all the symmetries that characterize the fundamental state[2].

To these one may add another kind of symmetry, based on covariant rather than on invariant principles. These do not preserve the nature of the events that are correlated, though they are quite useful in predicting the evolution of some nuclear reactions. Such are the so-called crossing relations, exemplified by the reaction (n,p) → (n,p-). No further reference to this type of symmetry will be made in the paper.

The *classical principles* are expressed directly in terms of events, and in that sense they are global, the events being the givens of observation which are independent of the way they may be correlated when viewed from the perspective of a theoretical model. They are represented by geometrical transformation groups, whose symmetries are correspondingly said to be *geometrical*. Neither the nature of the events, nor their probabilities, are altered in these transformations.

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[2] Cf. G. G. Ross: 4

To the extent that it makes sense to argue for the existence of an *observational substrate* common to all known interactions (by contradistinction with what one may call the *primeval substrate* that accompanied the universal birthing event), one may consider the 4-space continuum as the setting wherein all energy transformations occur, each kind typed by its own set of specific invariants. This inference is consistent with the fact that the classical conservation laws got from the geometrical principles of invariance: e.g. momenta, energy, etc. remain valid for all types of interactions. This further suggests that the classical dimensions of space and time are inseparable from the interactions that take place within that substrate, whence it follows that although the geometrical dimensions define the global context, they should not be thought of as independent of the specific interactions which obey the classical symmetries. Space and time are intrinsic features of interactions, and do not exist outside of them (Heelan, 1995).

On the other hand, the non-classical principles, which are interaction specific and therefore not global, cannot be expressed directly in terms of events. They are the so-called *dynamical principles of invariance*[3] which reflect internal symmetries[4]. They are used to define the transformation groups in terms of which the events observed in that particular stratum are correlated. In these, the nature of the events is altered, as well as their probabilities. These new symmetries are not characteristic of the background space-time, but of internal quantum numbers, such as the isotopic spin.

In spite of their relative remoteness from the events proper, invariance principles have assumed important roles in the formulation and in the validation of the theories designed to account for them. Traditionally, invariance principles have done two things: first, they clearly separated the "accidental" or contingent aspects of the observed phenomena, which are inherently dependent on local conditions, i.e. the "initial conditions", from the "laws of nature" which transcend the particular time and place. Second, the principles were derived *from* the laws which had been independently validated by observations and theoretical derivation (e.g. Poincaré's derivation of the classical invariances from the equations of electrodynamics and his realization that they formed a group which he called the "Lorentz Group"). Consequently to this, a new strategy was devised by Einstein in the Special Theory, and further exploited in the General Theory, which reversed the traditional relationship between the laws of nature and the invariance principles, deriving the former from the latter. This new strategy has fairly revolutionized physics and has led to rapid and impressive developments in quantum mechanics and in both nuclear and subnuclear physics[5].

Invariance principles appear as constraints on the formation of theories. For example, in the representation of the laws governing the interactions specific to a particular stratum, the theory is made to account for the observed limits to their application in a way that is consistent with the symmetries, so that the laws of motion and the states of the system are shown to obey the same symmetries.

In addition, the consequences of the laws within the mathematical context of the theory can be inferred from the principles of invariance, since the laws are required to remain invariant under certain kinds of transformation. This is the case, for example, with the

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[3] E. P. Wigner (1964): *Events, Law of Nature, and Invariance Principles*. In Wigner 1967, 45

[4] G. G. Ross (1985): chapter 2

[5] E. P. Wigner (1949), 5. In Wigner 1967

derivation of the conservation laws for both linear and angular momenta, for energy, etc., both in the Lagrange formulation of Classical Mechanics (Goldstein, 1951), and in the framework of Hilbert space in quantum mechanics (Bohm, 1951).

3.2. The Fundamental Interactions

The notion of a *field* was introduced to represent the fundamental energetic properties of nature and to describe the particles involved in the interactions between the fields. The fields are characterized by their transformations under symmetry groups. Four types of fundamental interactions have been identified in the laboratory: weak, strong, electromagnetic, and gravitational. Electromagnetic and weak interactions have been shown to be of the same type. *Interactions* may be defined as processes whereby energy is exchanged by real, i.e. observable, particles. This energy is not exchanged in continuous flows, but in discrete units or quanta, the *field particles*, which may be virtual or real, depending on the circumstances. Hence all known fundamental force fields are quantized. Consequently, interactions are best taxonomized in terms of the energy transferred, and measured in natural units (i.e. in electron-volts).

The various quantum fields may be thought of as complex forms or manifestations of the substrate field[6]. Since they are measurable, neither space nor time are given except in the context of some interaction, such as an actual measurement (Heelan, 1995). The folkloric notion of space- time as an independent, i.e. absolute, framework wherein interactions take place, such as Newton's absolute space-time, owes its origin to the range of the gravitational field which encompasses the whole material universe.

> (i) Ranking interactions on the basis of their observed strength, the weakest field is *gravitational*. The field particles that carry the interactions (the gravitons) have zero mass, whence their potentially infinite range. At very high energies (above 10^{19} gev), the gravitational field becomes a strong force, but there is no observational evidence to support this yet. At observable energy levels, the strength of the *effective gravitational field* is inferior to 10^3 gev.

Because of its infinite range and consequent ubiquity, the gravitational field pervades the whole material universe. Therefore all interactions take place within that underlying context, even in cases where the gravitational couplings are negligible by comparison with the local strength of some other field (e.g. in strong interactions). The gravitational field is also fundamental in the sense that the real particles, of which it is an endogeneous characteristic, all possess a gravitational charge, namely their rest mass, as its conjugate characteristic. This charge is an intrinsic property of matter and is inter-convertible, under suitable circumstances, with the radiant energy of which it is a condensed form, their energetic equivalence enshrined in Einstein's celebrated formula. And since field and matter both presuppose space and time, it is natural to seek the expression of both the radiant and the matter fields in the transformations of a common energy substrate, as in superGUT and ultimately, in a Grand Unified Theory (GUT) of some sort. What is guiding this search are the symmetries in the representation of these primeval interactions (Ross, 1985).

> (ii) The *electromagnetic field* has massless field particles as well (the photons) and thus a potentially infinite range (However, invariance considerations lead to families

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[6] G. G. Ross (1985): chapter 1

of field particles, many of which have mass and correspondingly shorter range (in cm): $10^{-8} \leq R_{em} \leq \infty$)

(iii) The strong interactions involve heavy field particles and corresponding extremely short range: $R_{sf} \approx 10^{-13}$ cm

(iv) Finally, the so-called weak interactions with the heaviest field particles and the shortest range of all the known interactions: $R_{wf} \approx 10^{-14}$ cm

Normally, the stationary state of a system should have the same symmetry as that of the laws of motion that govern it. In quantum mechanics, for example, one can always go from an asymmetrical state to another (e.g. oscillations of molecular structures (Anderson, 1972)). However, as systems become larger, symmetries may be broken, with the following consequences: (i) the internal structure of a piece of matter need not be symmetrical even if its total state is, (ii) the state of a large system (e.g. a crystal) does not have to have the symmetry of the laws that govern it.

Generally, the propagation and the interactions of fields are governed by symmetry properties. In the theories with local gauge symmetry, the only ones that are observationally effective or realistic, their perturbative character leads to a difference in the scope of their application, a situation first dealt with successfully in quantum electrodynamics by the strategy of renormalisation, which has now been extended to both strong and electroweak interactions, and even to gravitational field interactions (Ross, 1985). Furthermore, because of the substrate character of the space-time continuum, the representation of the various fields must be Lorenz invariant.

3.3. Interlevel Interactions

The project of tracing the origin of the different types of interactions to a single highly energetic field and thereby to unify them, is based on the observational evidence of the evolutionary character of the universe. In this perspective, the quantum fields are seen as different specifications of the primeval field, which became observable as the universe unfolded following the explosive event that marked its birth, whose traces are observable to this day [e.g. the background radiation].

In this evolutionary picture, as the density of the radiant energy decreased with the rapid expansion of the early universe, various energy strata made their local appearance, the most energetic ones coming first, being the most resistant to the "hard radiation" characteristic of the initial "fireball", revealing the symmetries that underlie the interactions internal to them (the intralevel interactions) and eventually the manner of their complexification. These fields are so many aspects of the processes of materialization of radiant energy. Some of them are internal to the material particles, and therefore closed and generative of cyclical processes, while others are external to them and therefore open to new influences, making complexification possible.

These external fields are the observable aspects of the particles' surrounds energized by their internal dynamics, and should therefore be considered endogeneous properties of matter. A related endogeneous characteristic inherent in the materialization of radiant energy is the appearance of charges sited in the particles themselves. These *endogeneous characteristics are intrinsic to the particles*, and are the *conjugates* of fields. They constitute the observational criteria of identity for the particles in fields of the same energetic character and enter into the representation of the interactions as quantum numbers[7].

At this point, it is worth remarking that an *elementary particle* is such only relative to the energetic level at which the interactions are observed, each stratum having its own complement of them. While a nucleon, say, is elementary relative to the strong interactions that bind it to other nucleons, it is not elementary in respect of the energy needed to penetrate to its inner structure where the three quarks interact with each other.

In energetic systems, complexification is initially the consequence of intralevel interactions obeying intrinsic laws of symmetry. These lead to the process of *symmetry breaks* from the underlying substrate, which is in turn responsible for the emergence of the conjugate characteristics of the new system (Ross, 1985).

(a) Evolution, as the defining characteristic of the material world, is marked by the emergence of new types of interactions whose natures are observationally determined by that of the endogeneous characteristics of the new system, themselves governed by its internal dynamical regime. The internal and external strata are therefore of a different energetic type, largely decoupled from each other, but interfaced by an energetically heterogeneous envelope B. The basic energetic architecture of such a system may be represented schematically as

$$\begin{tikzcd} & \Pi(\sigma) \\ B(\sigma) \arrow[ur] \arrow[dr] & \\ & \mathfrak{I}(\sigma) \end{tikzcd}$$

Here, σ is an "elementary" system, one whose internal energetic regime cannot be probed by the kind of interactions characteristic of its external energetic stratum [Anderson1972]; and where $\Pi(\sigma)$ and $\mathfrak{I}(\sigma)$ represent its *conjugate endogeneous characteristics*, the first being the *charges* which give it its objectual identity, for example (rest) mass, (intrinsic) spin, etc. and the second their corresponding conjugate *fields* which are responsible for the invariance of transformations characteristic of the external stratum.

(b) Field/particle interactions may be schematized as

$$\mathfrak{I}_\mu(\sigma_i) \underset{i \neq j}{\circ} \Pi_\mu(\sigma_j) = S(\Sigma)$$

where $\mathfrak{I}_\mu(\sigma_i)$ and $\Pi_\mu(\sigma_j)$ represent respectively the charges and fields of the interacting ith and jth elements. In quantum field theory, this interaction is represented as an interaction between fields of the same energetic type:

$$\mathfrak{I}_\mu(\sigma_i) \underset{i \neq j}{\otimes} \mathfrak{I}_\mu(\sigma_j)$$

In the interaction, there is the exchange of a field particle between the two systems σ_i and σ_j, $i \neq j$.

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[7] G. G. Ross (1985): 31

(c) Combining the previous two schemata, one can construct a schema for the ontogenic process for a complex particle having Σ an internal dynamical structure $S(\Sigma)$ whose origin is due to the intralevel interactions between its elements σ_i:

$$\begin{tikzcd}
 & \Pi(\Sigma) = \{ \pi_\mu \} \\
\Im_\mu(\sigma_i) \underset{i\neq j}{\circ} \Pi_\mu(\sigma_j) = S(\Sigma) \Rightarrow B(\sigma | \Sigma) \arrow[ur] \arrow[dr] & \\
 & \Im(\Sigma) = \{ f_\mu \}
\end{tikzcd}$$

Where Σ represents the emergent system, whose internal structure is the result of interactions between elements $\{\sigma_i\}$; $S(\Sigma)$ represents the resulting energetic regime internal to Σ, and $B(\sigma | \Sigma)$ is its energetic envelope. The nature and effects of $S(\Sigma)$ in the genesis of Σ are symbolized in this schema, where $S(\Sigma)$ is some form of closed, i.e. circular regime, whose effect is the creation of the energetic envelope $B(\sigma | \Sigma)$ interfacing the two energetic milieux and contributing to their relative decoupling. $\Pi(\Sigma)$ are the new (emergent) endogeneous characteristics that jointly constitute the external criterion of identity (i.e. an observational one) for Σ, while $\Im(\Sigma)$ represents its energized surround $E(\Sigma)$.

(d) From what precedes, we can easily get a schema for more complex Hierarchisation:

$$\begin{tikzcd}
 & \Pi(\Xi) \equiv \{ \pi_\mu(\Xi) \} \\
\{\Im_\mu(\Sigma_i) \underset{i\neq j}{\circ} \Pi_\mu(\Sigma_j)\} \equiv S(\Xi) \Rightarrow B(\Sigma | \Xi) \arrow[ur] \arrow[dr] & \\
 & \Im(\Xi) \equiv \{ f_\mu(\Xi) \}
\end{tikzcd}$$

3.4. Causal Relations

Intralevel causal interactions are the most familiar, being those of classical physics which is not concerned with energetic hierarchisation. They can be represented schematically as $\Phi(x_i)$. Its *grammatical (theoretical)* and semantic deployments are well understood, including the relation they bear to the relevant *observation space* (Farre, 1995). The mathematical syntax interfacing grammar and semantics is that of continuous linear functions.

By contrast, interlevel causal relations are little understood. If they were of a traditional type, they would be represented schematically as $\Phi(x_i, \xi_\nu)$, where 'x' and 'ξ' denote semantic variables whose ranges are to be found in different energetic milieux, one external to the system, the other internal to it (Baas, 1994).

However, considerable difficulties attend the articulation of these causal relations, due to the relative decoupling of the relevant energetic milieux. These difficulties have their origin in the fact that the semantic variables internal to the system, e.g. ξ_μ, cannot be projected onto their corresponding observation space in a manner consistent with the role they play in the validation of the morphology. More specifically, the validation of a morphology requires that the computed values of its semantic variables be measurable as well in the relevant context of observation, that is to say first, that for any a given computed value of a semantic variable ξ_μ, there corresponds a measure set $\boldsymbol{m}(\xi_\mu)$ and second, that the actually measured value of that variable fall within that set. The impossibility of doing this in the case of interlevel interactions leads to that of validating the phenomenology observationally (Wigner, 1963).

So, a "traditional" schema such as $\Phi(x_i, \xi_v)$, with 'x' and 'ξ' denoting semantic variables belonging to different energetic milieux, is not applicable to interlevel relations: there is no direct connection between the dimensions of the internal dynamical process and those needed to represent the intralevel interactions taking place in the external milieu. The causal laws that represent interlevel causal interactions cannot be expressed directly in terms of observables. and the "internal" and the "external" languages are not translatable into one another.

The representation of the bridging of the energetic gap is likely to require three distinct steps: first, a suitable representation of the internal dynamical regime thought to be relevant to the conjugate characteristics of the emergent system; second a representation of some phenomenology tokenized in the external milieu; and third some mathematical device to transform key features of the former dynamical structure into those of the latter. While the first two exhibit the symmetries characteristic of their stratum; the third represents a symmetry break between the first two, and thus is not likely to represent any process analyzable in terms of observables, i.e. it has no inherent semantics. An example of this mathematical strategy has recently been pioneered by Schempp in the case of NMRI, and should prove fruitful for the representation of the functional aspect of interlevel interactions (Schempp, 1996).

4. CODA

The dominant features discussed in this paper are: first, the discovery of the energetic stratification of nature; second, the new and essential role played by the principles of invariance in the derivation of the laws that govern the interactions internal to individual strata (intralevel interactions); third, what is important are not so much the equations as the solutions in which the symmetries are embedded; fourth, the energetic hierarchisation of matter presupposes the action of causal interlevel interactions to bind them together in predictable ways; fifth, that these strata are largely decoupled, meaning that we don't know how to represent them despite the fact that they are deterministic and thus predictable as to type. It is therefore to be expected that the representation of intralevel relations is not the whole story, and that the physics underlying renormalization owes something to interlevel relations.

From these, one may infer that science is at the dawn of a new era, one in which the focus will turn to the interactions that bind the different strata together, namely to the *interlevel interactions*. The problems inherent in this task are enormous, primarily because we do not have either the conceptual or the mathematical tools needed to articulate them. There are at present two chief mathematical instruments in use: the computational techniques which are good for the modeling of complex intralevel interactions (as in renormalization), or for the simulation of particular features of some system's behavior, as in robotics. These techniques however can't address the issues raised by the stratification of hierarchies, primarily because their use demands an energetically homogeneous context (Penrose, 1994). The other mathematical strategy is newer, and relies on group transforms to bridge the gap between the different energetic types. Schempp's forthcoming book provides a telling illustration of what such mathematical instruments can do.

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