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Entropy, Deterministic Chaos, and New Forms of Intelligibility: A Shared Frame of Reference for Physics and Psychology

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***Abstract*— Prigogine's theory of dissipative structures provides a general account of entropy-driven self-organized transitions through hierarchies of structures separated by discontinuities. The theory encompasses a wide range of evolving systems throughout nature and culture. Possibilities for operationalizing a new collective rationality spanning physics and psychology emerge from Prigogine's emphases on two distinct senses of probability, on the concept of the sufficient statistic, and on the role and limitations of the Poisson distribution in formulating a "nonlinear master equation." Unnoted by Prigogine are correspondences of all three of these issues in the mathematical foundations of statistics and measurement established in the works of Ronald Fisher and his student, Georg Rasch. The three areas of correspondence inform models enabling specifically metrological approaches to quality-assured quantification across the sciences. Prigogine's sense of "deterministic chaos" is re-expressed in measurement terms as stochastic invariance and the need for "a supplementary parameter" augmenting the Poisson distribution is related to a rating scale model of measurement. Considering these connections, this paper proposes that what Prigogine anticipates as a "new intelligibility" and a new science of "collective rationality" could be pragmatically operationalized in a new metrological infrastructure, one made coherent by the generality of entropy-driven nonequilibrium processes.**

***Keywords*— entropy; nonequilibrium processes; measurement; probabilistic models; stochastic invariance**

I. Introduction

Haynes and colleagues remark that:

> *Since the 1980s, most social science applications of entropic methods have separated themselves from intriguing but none-too-useful analogies with thermodynamics and statistical mechanics, concentrating instead on foundations in probability and statistics. We applaud this trend as a maturation of social science modeling and urge researchers to distinguish statistical entropy information from thermodynamic entropy, referring to thermodynamic ideas only when doing so is clearly necessary in ecological or nature-human interface studies.* [1] (p. 41)

One can hardly disagree that social science's entropic analogies with thermodynamics are immature. Georgescu-Roegen's 1971 book, *The Entropy Law and the Economic Process* [2], like Bailey's 1990 *Social Entropy Theory* [3], not only did not lead to a new consensus on models and methods, but difficulties encountered in substantively connecting physical entropy with evolving social and psychological systems rendered many of its uses empty metaphors [4-7]. Although the theory of entropically dissipating nonequilibrium processes is deeply rooted in the early works of Gauss, Gibbs, Fourier, and Boltzmann [8], the equilibrium conception of economic processes proved a more tractable, though more limited, integration of the nineteenth century's mutually interdependent but polarized labor theory of value and marginalism paradigms [9] - [10].

Key opportunities for demonstrating essential points of contact with theoretical and methodological fundamentals have gone unremarked, however. This has understandably obstructed abilities to imagine, plan, and obtain practical results living up to the expectations generated by the original prospects for a new science. Even so, most of the rest of the authors of chapters in the book containing the Haynes paper appear to disagree with Haynes et al.'s statement, as they all pursue the intriguing analogies Haynes disavows.

Those chapters, however, can be interpreted as making Haynes et al.'s point for them. They do so by proceeding in the usual manner from the typical assumptions of the methods employed in the social sciences, and so do not focus on substantiating important aspects of the analogy with thermodynamics. This has been the predominant manner of proceeding in a large volume of research conducted over the last 50 years extending ideas and methods involving entropy and complex systems from the natural sciences into psychology and the social sciences.

This trend began when the phenomena of noise-induced, entropy-driven physical phase transitions were found to have clear analogues in chemical and biological development and evolution [11] - [18]. This work provides a platform for imaginative explorations of a new dialogical kind of intelligibility integrating the discourses of the natural and human sciences [3], [19] - [36]. In initiating these investigations, Prigogine provides a rare example of

Nobel-level technical expertise combined with a best-selling book translated into twelve languages [37], [38]. Though much has been said in this context by way of conjectures, theorizing, and descriptive expositions, rich potentials for practical methods and results incorporating Prigogine's [39] sense of a paradigmatically "new rationality" have yet to be fulfilled.

That may change as both a general philosophical worldview and its specific mathematical technicalities are articulated in methodological terms better able to inform the conduct of a wide variety of research programs across the sciences. Given the long history of efforts failing to improve the human condition or doing so only to markedly limited extents [40], it is essential that we foreground the role of uncertainty and the potential, with the irreversible passing of time, for all conclusions to be retrospectively evaluated as premature and hasty [41], [42]. This entails an ethos of keeping the conversation that we are alive, open to new experiences, and that empowers participants in dialogue to negotiate common understandings in unique local circumstances. The goal here then is limited to some modest initial explorations of the possibility that there may be productive mathematical modeling connections to be made between nonequilibrium processes and measurement, and that these connections may be important to richer fulfillments of the potentials that many have discerned in thermodynamics for so long.

A start in this direction draws on Prigogine's theory of entropy-dissipating structures, where order increases as entropy production declines in relation to the maximum possible entropy. This current effort expands on recent research connecting entropy, information, and measurement [43] - [47]. Although that body of work is not integrated with nonequilibrium thermodynamics, it remains highly relevant to the design and implementation of metrologically traceable systems of distributed cognition [43], [44], [48] - [57].

Substantiating the analogy from thermodynamics requires a clearer understanding and operationalization of probability as an issue of central importance for characterizing social and psychological phenomena in terms of dissipative structures. Prigogine repeatedly emphasizes, but does not clarify, a distinction between two senses of probability. One of these obtains in deductive population statistics motivated by sampling problems, while the other is a sense of probability not resigned to making do with incomplete information, but which instead expresses the structure of natural law. This is a matter of central importance. After fleshing it out, Prigogine's "nonlinear master equation" is re-expressed to connect it with the form of additive conjoint, log-interval models of measurement [58] - [67] supporting quality-assured unit definitions and instrument traceability [51], [54], [68].

Prigogine's sense of the way dissipative structures of all kinds self-organize and evolve through hierarchically complex and discontinuous levels of complexity is then explicated in the context of developmental psychology. Discussion focuses on the cognitive and operational difficulties experienced in shifting individual thought and institutional policies away from automatic Cartesian assumptions of individual volition and centralized planning to the initiation of Hegelian, distributed, multilevel, embodied cognitive systems [69] - [76]. These difficulties themselves are evidence of the power exerted when individual minds are embedded in and integrated with symbolic ecologies. The fluidity of virally contagious automatic associations makes the modern Western dualistic and Cartesian worldview a formidable barrier to initiating a new unmodern nonWestern, nondualistic, Hegelian worldview embedding collective rationality in its institutional infrastructures. Thus, neither Prigogine nor Piaget fully succeeded in thinking through their basic Cartesian worldviews to transform their hidden assumptions into objects of operations at a higher order level of complexity [77], [78]. Their failures largely follow from their lack of attention to the need to solidify strategic alliances and expand networks enabling stakeholders to advance their interests more effectively via collaboration than they could in isolation [79] - [82].

Moving in this direction of ecologizing instead of modernizing [83] - [85] then entails contradicting Haynes et al.'s [1] recommendation that researchers take up "referring to thermodynamic ideas only when doing so is clearly necessary in ecological or nature-human interface studies," since the point is to cease merely describing nature and ecosystems, and to instead actively constitute human nature's integrated organism-environment units of survival, being the change we want to enact. Such lived paths substantiate developmental psychology's focus on play in environments providing ample infrastructural learning opportunities [75], [86] - [88] and correspond with the playfulness of subjective experience in language use [89] (p. 104), and with the flow of learning in the history of science [90] - [93].

Universally accessible cognitive infrastructures embedded in the social environment induce the operationalization of individuals' latent skill potentials [87], [88], [94], [95] because "organism and environment are inseparable in cognitive development" [96] (p. 646). Simply put, the question is one of augmenting individual intelligence with smart contexts [97], of obtaining "brilliant results from average people managing brilliant processes" (Cho, quoted in [98], p. 84), and recognizing that "cultural progress is the result of developmental level of support" [99] - [101]. In this context, recognizing the unity of the organism and its environment as the focus of natural selection [94], [102] - [104], it becomes apparent that common languages like the SI units constitute an infrastructural capacity essential to the advancement of science and the economy. As will be shown in the contrast of deductive probabilities and inductive likelihoods, conceiving the organism-environment as the unit of survival and adaptive evolution leads to a sense of "probabilistic epigenesis" [88] useful in imagining new possibilities for the future.

They obtain that status by enabling us to think the same thoughts in a coordinated way without having to communicate directly [105], [106] (pp. 247-257) [107] - [115]. As Hayek [116] (p. 88) [117] put it,

The problem is precisely how to extend the span of our utilization of resources beyond the span of the control of any one mind; and, therefore, how to dispense with the need of conscious control and how to provide inducements which will make individuals do the desirable things without anyone having to tell them what to do.

Hayek's specification of inducements will prove to be key in addressing this problem of how to embed a collective rationality in the infrastructural cognitive supports provided by the external social environment. Prigogine [118] (p. 504) similarly remarks on how models of nonequilibrium processes surpass the capacities of traditional equilibrium models in economics, saying that:

The interest of this class of models is that they enable us to make the interplay between the actors and the constraints of the environment more transparent…. Let us emphasize the importance of such models for social sciences in order to make the decision mechanisms more transparent in a democratic society: we have here an example of a process of evolution in which science and collective rationality may interact in a constructive way. Perhaps this will be a way of demythologizing the process of collective decision making, without negating its complexity. Models alone will of course not be a substitute for political decision making, but they may help to make their implications more explicit.

The models and "new laws of nature" Prigogine [119] holds as emerging at "the end of certainty" require recognizing, accepting, and integrating the uncertainty entailed by evolving entropy-dissipating systems. In these systems, three discontinuous levels of complexity are simultaneously enacted: a concrete within-individual micro level, an abstract individual meso level, and a formal population macro level. Prigogine and Stengers [38] (p. 300) say:

…an essential characteristic of our scheme is that it does not suppose any fundamental mode of description; each level of description is implied by another and implies the other. We need a multiplicity of levels that are all connected, none of which may have a claim to preeminence.

As a result of his ethnographic study of experimentalists, metrologists, and theoreticians in microphysics, Galison [120] (p. 143) similarly proposes an "open-ended model" that is "tripartite in allowing partial autonomy to instrumentation, experimentation, and theory," and that leads us to "expect a rough parity among the strata—no one level is privileged, no one subculture has the special position of narrating the right development of the field or serving as the reduction basis." Galison [121] (p. 46) explains, remarking on how "representing meaning as locally convergent and globally divergent seems paradoxical" while at the same time recognizing that:

It seems to be a part of our general linguistic ability to set broader meanings aside while regularizing different lexical, syntactic, and phonological elements to serve a local communicative function. So too does it seem in the assembly of meanings, practices, and theories within physics. [121] (p. 49)

That is, everyday language does not typically use abstract phonemic and grammatical standards to impose uniform idealized conceptions on unique local circumstances. Instead, arbitrary abstractions set up as consensus standards serve as the media through which shared understandings are negotiated by relating multifaceted ideas to concrete things. In everyday language, the semantic triangle of ideas, words, and things functions as an assemblage packaging a heterogeneous array of structures, functions, and fluctuating circumstances in intuitively accessible linguistic systems.

Semiotics has then expanded into ecosemiotics, biosemiotics, and cybersemiotics as the role of language as the irreducibly complex vehicle of thought has focused interest on transdisciplinary models of science [122] - [129]. Analogous senses of multilevel complex assemblages have been explored and documented by other investigations in the history of science emphasizing the roles of measurement standards and instruments as mediating social relations, theory, and data [81], [82], [106], [130] - [152]. Though multilevel complexity is difficult to grasp conceptually, everyday language use and repeated daily measurements of time, distance, temperature, etc. involve practical experience in how it works.

In like fashion, in psychometrics, Guttman [153] (pp. 79-81) also emphasizes that three levels are employed simultaneously when he distinguishes informal everyday language from formal technical terminology and from mathematical symbolization, en route to articulating a theory and practice of cumulative science. Each of Guttman's levels can be seen as implying semiotic distinctions between levels for concrete things and data, abstract words and instruments, and formal ideas and theories within them. Wright [154], another psychometrician, explicitly expands on the levels of complexity offered in Peirce's semiotics to describe the evolution of understanding in science and measurement, while Stenner and Horabin [155] describe the evolution of construct theories as progressing from intuitions to data to prediction. And to underscore the multilevel functioning of cognitive operations, developmental psychology recognizes that people utilize multiple levels of cognitive complexity at the same time, and typically employ the lowest level of performance allowed by the environment [96], [156].

The uncertainties entailed by the chaotic dynamics characterizing these levels of complexity set limits on the extent to which the interplay between the individual and its environment can be made more transparent. That transparency will never be perfect, but much can be done to improve on the obscurities and confusions dominating today's systems by recognizing, accepting, and acting on the all-pervasive ubiquity of uncertainty:

> *...even in classical physics we get randomness and unpredictability.... pure mathematics, in fact even elementary number theory, the arithmetic of the natural numbers, 1, 2, 3, 4, 5, is in the same boat. ... So if a new paradigm is emerging, randomness is at the heart of it.* [157] (p. 13)

We are well past the point in time at which the historic importance of uncertainty as a paradigm-setting principle [157] - [163] ought to have infused every level of discourse in every field of human endeavor. Given that his proofs on the irreducible incompleteness and inconsistency of self-referential systems, and his "discovery that there are arithmetical truths which cannot be demonstrated formally" [164] (p. 101), have had little effect on the practices of mathematicians, it is not surprising that Gödel wrote a letter to his mother expressing his disappointment that his work had not impacted mathematics the way that his friend Einstein's work had impacted physics [157] (p. 13). Though it will have taken much longer to arrive, Gödel's day may yet come. Gödel's proofs inspire confidence in the validity and truth of the shift in the conception and practice of scientific method entailed by the foregrounding of uncertainty advocated here [165] (p. 52).

That confidence will be needed as the limits on knowledge become even more complex. It will be imperative that we move beyond systematic integrations of concrete, abstract, and formal levels to yet higher orders of complexity. We tend to devalue and brush aside paradoxical complications, ambiguities and inconsistencies in daily life, such as the contradictions obtaining in obeying or disobeying a parental command to stop acting like a child, or those involved in taking the initiative while not crossing boundaries.

In this vein, contrary to Kuhn's [166] emphasis on convergent thinking in coherent paradigms, Prigogine and Stengers [38] (pp. 307-309) take issue with Kuhn's sense of normal science, emphasizing the way undercurrents of nagging discrepancies persistently appear, are minimized or ignored and disappear, and re-appear in unexpected contexts, in the history of science. Similarly, in a complementary fashion, others have shown healthy scientific fields to be productive as a result of perspicacious divergence in thinking, where disagreements provoke learning, investments in demonstrating proofs, and developments toward unexpected insights [121] (pp. 46-49, 843-844) [167] - [170]. Recognizing that universally uniform consensus on fully determined facts has never been and never will be achieved, Prigogine and Stengers [38] (p. 299) conclusively assert that "the epoch of certainties and absolute oppositions is over." Indeed, nothing is more certain than uncertainty [171].

Agreeing to disagree in productive ways becomes ever more important in the contexts defined by systems of systems at the metasystematic level of complexity, by supersystems at the paradigmatic level, and by systems of supersystems at the cross-paradigmatic level [90], [91], [172] - [174]. The provisional clarifications that might be achieved by explicitly addressing uncertainty and modeling it in practically applicable stochastic formulations might lead toward empowering transformations [85] of today's disempowering organizational paradoxes [175].

We here intentionally seek to define and create institution-level infrastructures for ecologized economies of thought at a paradigmatic level [176]. This intention is a continuation of Prigogine's [15] (p. 12) introduction of mathematical methods for characterizing "a whole hierarchy of structures separated by discontinuities" enabling "a concrete, unified description of the macro-world," where "the concept of stability really reconciles the unity of laws with the existence of well-defined levels of description." These methods must then integrate individual mental operations with the external environment's infrastructural supports at multiple discontinuous levels of complexity, in a manner replicating today's existing integrations of scientific, legal, market, and communications networks and standards [108] - [111], [177] - [181]. In so doing, we aspire to fulfilling Prigogine's goal of a new collective rationality.

II. Distinguishing Probability from Likelihood

Prigogine [17] distinguishes between two kinds of probability while arguing that transitions through "a hierarchy of structures separated by discontinuities" are entropically driven by spontaneous reorganizations of functions—fluctuations—and that "this conception is applicable to a large number of situations, including the functioning of cognitive structures envisioned by Piaget" [17] (p. 263) [19], [39], [118], [182] - [187]. Brooks and Wiley [11] (p. 356) concur, saying, "The second law [of thermodynamics] is thus more than the natural law of energy flows; it is the natural law of history" [25]. Prigogine [17] (p. 263) [16], [38], [119] concludes by saying, "We are perhaps moving towards a new discipline which will inherit from physics the cares of the world, of quantitative description, and from classical metaphysics the ambition of finding a coherent global image that would include man."

At the physics end of this new discipline, Prigogine argues that, from his perspective, in quantum theory "the basic quantity is no longer the wave function corresponding to a probability amplitude, but probability itself. …Probability is no longer a state of mind due to our ignorance, but the result of the laws of nature" [119] (p. 132), [17] (p. 262), [188] (p. 5). These laws comprise a "new form of intelligibility as expressed by irreducible probabilistic representations … [that] deal with the possibility of events, but do not reduce these events to deductible, predictable consequences" [119] (p. 189).

Prigogine's sense of a different, nondeductive kind of probability directly expressing laws of nature independently reproduces the inductive likelihood functions Ronald Fisher [189], [190] contrasted with deductive population statistics' probabilities. Fisher [189] (p. 367) wrote:

The conclusion is drawn that two radically distinct concepts, both of importance in influencing our judgment, have been confused under the single name of probability. It is proposed to use the term likelihood to designate the state of our information with respect to the parameters of hypothetical populations, and it is shown that the quantitative measure of likelihood does not obey the mathematical laws of probability.

Duncan and Stenbeck [191] (pp. 24-25) argue that this contrast of likelihood and probability marks an essential difference between scientific and statistical models:

The main point to emphasize here is that the postulate of probabilistic response must be clearly distinguished in both concept and research design from the stochastic variation of data that arises from random sampling of a heterogeneous population. The distinction is completely blurred in our conventional statistical training and practice of data analysis, wherein the stochastic aspects of the statistical model are most easily justified by the idea of sampling from a population distribution. We seldom stop to wonder if sampling is the only reason for making the model stochastic. The perverse consequence of doing good statistics is, therefore, to suppress curiosity about the actual processes that generate the data.

Duncan and Stenbeck [191] (p. 23) [192] say they emphasize this distinction between statistical models and scientific models "with all the rhetorical force we can muster." A large chorus of others writing before and since [67], [193] - [203] expand on this theme. Guttman [204] (p. 329), for instance, states that "Measurement theory…deals with the construction of structural hypotheses rather than with inference from samples." Statistical models describe population-level data distributions to support deductive inferences from samples. In this paradigm, models are fit to data, prioritizing the maximization of explained variance or the minimization of p-values in significance tests. Model-data mismatches are rectified by modifying the model, often via the addition of multivariate interactions. The hypothesis of a reproducible unit quantity that remains invariant across instruments and samples is not formulated or tested.

Scientific models, in contrast, prescribe the form of individual level response functions to inductively infer the definition and comparison of generally applicable unit quantities bound by uncertainty. In this paradigm, data are fit to models specifying the univariate structure of quantitative measurements. Model-data mismatches are rectified by modifying the data, not just in the sense of the particular observations included in tests of the quantitative hypothesis but more fundamentally in the sense of attending to the content of the questions asked.

Ronald Fisher [189] developed the mathematical basis for the contrast between (a) scientific measurements, where individual observations comprise a sufficient statistic (a count or sum score) extracting all available information from the data, and (b) statistical analyses in which group-level means and standard deviations are sufficient for reproducing normal distributions. These concepts and distinctions remain today just as confused and blurred as they ever have been. Explicit mention of the differences between deductive sampling probabilities and inductive response likelihoods is lacking in most examinations of probability in measurement modeling. When they are mentioned, the differences are minimized.

For instance, a recent text on metrological infrastructure [205] (pp. 46-47) notes that two mutually inconsistent versions of probability co-exist in the GUM (Guide to the Expression of Uncertainty in Measurement) [206]. One version involves a "conventional" focus on event frequencies, and the other, subjective degrees of belief. Though not referred to as such, this distinction plainly involves the difference between deductive inferences motivated by sampling problems and inductive inferences motivated by response processes. This internal inconsistency is said to be "harmless" and that, when a decision between them must be made, the GUM endorses the conventional view.

In another example [207] (pp. 39-40) in which the differences between inductive likelihood functions and deductive sampling probabilities are noted, it is recognized that "the likelihood function is not a probability distribution" and that "maximum-likelihood estimation is not a probabilistic estimation." But the overriding assumption of probability as singularly involving sampling problems leads to the dismissal of the likelihood function as "not fully convincing" and largely irrelevant to measurement modeling. When inductive inference problems are addressed, they are typically taken up in Bayesian terms [207] (pp. 48-54), and in the course of identifying the value of the measurand from the measurement system's observed output (i.e., during a restitution or reconstruction process) [208], [209].

The inferential connection made in restituting the measurement value in relation to an SI unit standard suggests a potentially productive point of entry for expanding the conceptualization and operationalization of inductive inferences and response process likelihoods into measurement systems featuring quality-assured metrological traceability [51] (p. 48), [43], [68] (pp. 71-74). An influential source of possibilities for that kind of an expanded appreciation of likelihood functions in metrology are found in the works of Rasch [63], [65], [210]. After studying in 1934-1935 with Ronald Fisher in London, and with the econometricians Frisch and Tinbergen in Oslo, Rasch formulated probabilistic models for measurement blending Fisher's emphasis on the sufficiency of individual-level response processes with Frisch and Tinbergen's application of Maxwell's method of analogy [111]. Rasch

[63] (pp. 110-115) structured the form of his models via an analogy from Maxwell's analysis of Newton's Second Law, incorporating the form of lawful regularity into the model parameterization.

In taking this approach, Rasch's measurement modeling concepts stand in complete opposition to the models and methods associated with Item Response Theory (IRT) [211], as has been repeatedly asserted by all of the major proponents contributing to the advancement of Rasch's perspective [67], [193], [201] - [203], [212] - [218]. As Linacre [219] (p. 926) put it, "The Rasch dichotomous model is a derivation from measurement axioms. It has nothing to do with the normal ogive model" used in IRT. Even IRT advocates admit that "The [IRT] theta-scale, or any linear transformation of it, however, does not possess the properties of a ratio or interval scale, although it is popular and reasonable to assume that the theta-scale has equal-interval properties" [220] (p. 87).

Going along with the misconceived association of Rasch's perspective on measurement modeling with IRT simply because it is "popular and reasonable" amounts to nothing more than fallaciously appealing to expert authority, begging the question, equivocating, and appealing to popular opinion, all of which unscientifically assume something is true in the absence of a logical argument or evidence [221] (p. 20).

Rasch's principled perspective on designing instruments with the intention of empirically fulfilling explanatory ideals to fit-for-purpose quantitative uncertainty tolerances accords with

- Kuhn's [222] (p. 219) historically informed perspective that "The road from scientific law to scientific measurement can rarely be traveled in the reverse direction;"
- Butterfield's [223] (pp. 16-17, 26, 96) sense of scientific advances not being based in primarily empirical accumulations of observed data but requiring a geometrical "thinking cap;" and with
- Kant's [224] (p. 20) perspective that science does not follow "nature's leading strings," but compels nature to answer questions of reasoning's own determination in an unfolding dialogue.

Appropriating without citation Tinbergen's application of Maxwell's method of analogy [111], [225], [226], Rasch conceived of measurement as a probabilistic projection of the form of a scientific law, using it as a means of seeing whether experience might be amenable to that kind of organization. As Rasch wrote:

> *...the acceleration of a body cannot be determined; the observation of it is admittedly liable to ... 'errors of measurement', but ... this admittance is paramount to defining the acceleration per se as a parameter in a probability distribution -- e.g., the mean value of a Gaussian distribution -- and it is such parameters, not the observed estimates, which are assumed to follow the multiplicative law [acceleration = force / mass]."*
>
> *Where this law can be applied it provides a principle of measurement on a ratio scale of both stimulus parameters and object parameters, the conceptual status of which is comparable to that of measuring mass and force. Thus, ... the reading accuracy of a child ... can be measured with the same kind of objectivity as we may tell its weight* [63] (p. 115).

Rasch here built on Ronald Fisher's [103] (pp. 103-104) point that, "because all laws of natural causation were essentially laws of probability, the predictability of a system has the same basis in the natural as in the social sciences" [227] (p. 289). In accord with Prigogine's sense of "deterministic chaos," Fisher held that, "far from being contradictory, the notions of probability and determinism are intrinsically related" [227] (p. 290). The key distinction between likelihood and probability is maintained here in that the Gaussian distribution referred to by Rasch concerns the errors of measurement associated with each individual estimate, whether of stimulus or response parameters. All further references here to probabilistic models of measurement assume this distinction is understood.

Wright [228] (p. 32), the foremost proponent of Rasch's ideas from the 1960s through the 1990s [229], [230], accordingly says that what Rasch accomplished is "a definition of measurement, a law of measurement. Indeed, it's *the* law of measurement." Probabilistic conjoint models [59], [61], [231], [232] operationalizing this law of measurement have informed several decades of research and practice in the development and deployment of quantitative systems for high stakes admissions, graduation, certification, and licensure contexts [233], [234], in classroom applications facilitating formative feedback [235] - [241], in the context of Piagetian developmental psychology [242] - [250], in adaptive and AI instrument adminstrations [251] - [253], and others involving tens of millions of measurements annually [254] - [258], in education, health care, sustainability, and other fields.

Research in the domain of dissipative structures, however, has not incorporated the structure of natural law into the form and function of measuring instruments calibrated to defined unit quantities. Prigogine stresses the empirical, phenomenological groundedness of the new sense of probability he has identified, and notes that it is not the same thing as the probabilities deduced in accommodating the limits on knowledge imposed by statistical sampling problems. But Prigogine's research and that of others applying his ideas does not specifically model and evaluate invariant structural dimensions of collective action projected by and estimated from individual observations. Neither are these experiments conducted with the aim of calibrating tools intended for distribution throughout networks of end users whose decisions and behaviors constitute the collective rationality that was modeled.

On the contrary, the probabilistic methods implemented in applications of the theory of dissipative structures are formulated and applied in a deductive and descriptive statistical manner that neither identifies nor calibrates the hypothesized collective dimension on the basis of individual response likelihoods. The promised laws of nature are confirmed only in summary statistics describing processes from the outside in and top down, not in distributed measurements inscribing processes from the inside out and bottom up. Not being formulated in terms informing active participation in modeled processes on mass scales, the statistically described collective rationality has no medium of implementation. We now turn to how that kind of formulation might be achieved.

III. Re-Expressing Prigogine's "Nonlinear Master Equation" as a Probabilistic Model of Measurement

Prigogine's [16] (pp. 115-119) [188] (pp. 28-34) "nonlinear master equation" can be restated as a probabilistic model of measurement, one that "belong[s] to the same class that metrologists consider paradigmatic of measurement" [50] and that provides "a specifically metrological approach to human-based measurement" [54] (p. 26). The potential for a meaningful restatement of the master equation follows from Prigogine's distinction between empirically descriptive phenomenological equations and theoretically prescriptive master equations, which then provide a model of a natural law. Prigogine's emphasis on individual-level processes is substantiated in terms of the same Poisson and Markov processes employed in probabilistic measurement. Prigogine stakes the objectivity of the measurements made on the demonstrable generality in nature of Poincare resonances, which are taken as the basis of a structural analogy to cognitive and social phenomena.

A. Poisson Limitations and the Need for a "Supplementary Parameter"

Prigogine [16] (pp. 116-117) remarks on shortcomings of the Poisson distribution limiting its relevance to stable systems. This limitation makes it necessary to bring in a "supplementary parameter scaling the extension of the fluctuations" to make it apply in unstable systems [16] (p. 117). Fluctuations compromising the stability of the macroscopic state may provoke a transition to a different level in a discontinuous hierarchy. But the appearance of a physical instability depends on fluctuations of a critical size, as they behave differently at different size spatial extensions: "only fluctuations of *sufficiently* small dimensions obey Poisson statistics" [16] (p. 117; emphasis added). Prigogine then remarks that "this is a very important result because it implies that, conversely, only fluctuations of a *sufficient* extension can attain enough importance to compromise the stability of the macroscopic state considered" [16] (p. 117; emphasis added).

Prigogine and Allen [188] contrast the applicability of the Poisson distribution and the law of large numbers in phenomenological equations for systems near equilibrium with the lack of an identifiable relation between them in nonlinear systems far from equilibrium. They say:

> *…the identification between these macroscopic equations and the first moment equations may become completely incorrect, as the probability distribution may cease to be sharply peaked, in which case the law of large numbers no longer applies. The probability distribution may, for example, become double humped, in which case the average value of a variable and its variance become meaningless quantities, since they completely fail to define the double-humped curve* [188] (pp. 26-27).

Though no mention is made of the concept of statistical sufficiency, Fisher's [189] proof of the meaninglessness of the average and its variance outside of the context of a normal Gaussian curve is clearly invoked. Also implicated is the idea of identified models, developed in econometrics by Frisch, Koopmans, and Reiersøl as a criterion for the practical applicability of models intended to guide real-world implementations [259], [260]. Though Rasch makes no mention of model identifiability, Koopmans and Reiersol thank him for his input in "fruitful" discussions, and he effectively applied the concept via his emphasis on sufficiency [111], [216].

The nonlinear transitions of concern correspond in psychology to changes from (a) counts of one kind of process, or a category of ratings accumulated across observations of performances within a particular level of difficulty, to (b) counts of another kind of process, or ratings concerning performances at a higher level of difficulty, where what Prigogine [16] (p. 117) refers to as the "supplementary parameter" represents the thresholds of the transitions across levels. Models incorporating this kind of a parameter are widely used in assigning partial credit in the scoring of learning outcomes, development and growth, and in rating performances, attitudes, behaviors, and skills [261] - [264]. As suggested in making the distinction between scientific and statistical models, a matter of fundamental importance in both Prigogine's theory of dissipative structures and measurement theory concerns the sufficiency of the transitions from one category to another.

As he stated in an autobiographical passage, Rasch [65] (p. 66) did not appreciate the scope of what he had accomplished in formulating the measurement model associated with his name until he was provoked by Frisch to see that he had answered the question:

> *Which class of probability models has the property in common with the Multiplicative Poisson Model, that one set of parameters can be eliminated by means of conditional probabilities while attention is concentrated on the other set, and vice versa?*

The inferential separation of parameters in this class of probability models allows person or object measurements to be compared independent of the particular questions or indicators used as the medium of observation [264] - [266] [267] (pp. 52-55). Some years after Frisch's astonishment at the "disappearing parameter," Rasch [210] (pp.

104-105) [65] formulated the epistemological concept of specific objectivity to characterize the quality of the inferences and comparisons supported by measurements modeled in this way.

Rasch intentionally structured his models in the form of Fisher-Darmois-Koopman-Pitman additive exponential models because these admit the observed score summed from Poisson counts of correct answers or performance/frequency/attitude ratings as a sufficient statistic for the individual-level response process likelihoods [65], [268] - [277]. Prigogine made use of these distributions for much the same purpose, but without structuring the model in the form of Maxwell's analysis of Newton's second law, as Rasch did.

What Prigogine calls "noise-induced phase transitions" are shifts from one categorical state of existence, cognition, moral bearing, mode of being, form of life, or species, to another. These take place as the uncertainty associated with being at a given level increases, the likelihood of staying at that level decreases, and the likelihood of a shift to a higher level increases. This is what happens in sociocognitive measurement when development away from one level makes a person's status increasingly ambiguous before it settles into a new stability at a higher level.

Prigogine and Allen [188] (pp. 24-28) give a simple example of

> *…how the probabilistic and phenomenological approaches are linked and how in the description of a nonlinear system whose basic mechanisms define a Markov process, the detailed study of the behavior of fluctuations can give an important new insight into the phenomena encountered.*

The simple example given notes that the Poisson distribution and the law of large numbers apply as long as the system is stable and the probability (likelihood) is peaked around a single value, but as a bifurcation point is approached, where the dominance of one form of life (species, culture, technology, ability level, health status, etc.) declines in relation to the increase of another, the variance diverges and the distribution spreads into a double-peaked probability curve. But the variance diverges in a way that leads to "a new type of law of large numbers," where the overall probability distribution is flattened, and "we can trace the line of coexistence between the two solutions on the basis of the stochastic potential" [188] (p. 27). This new type of law of large numbers corresponds to a rating scale model of measurement [261] - [264].

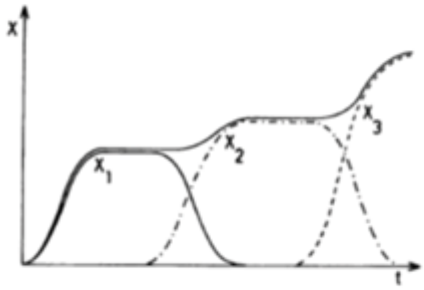

Figure 1. Evolutionary succession of species in the same niche [188] (Figure 1.15, p. 30).

This correspondence is partially illustrated by Prigogine and Allen's [188] (p. 30) Figure 1.15 (Figure 1 here) and rating scale category transition likelihood curves (Figure 2). (Though typically referred to as probability curves, in an effort at maintaining a more rigorous distinction between probabilities and likelihoods, they will be called likelihood curves here.) Each set of curves in Figure 2 informs an interpretation of a single person's (or any group's mean) measurement in relation to a single test, assessment, or survey item. Person measurements lower than an item's calibration are to the left of center in each figure, and measurements higher than the calibrations are to the right. The further to the left a measurement is, the less likely a fully correct or highly agreeable response is, as the question asked is more difficult than the person is able. Conversely, as measurements increase, moving horizontally further to the right, the more likely successful or agreeable responses become. As shown in the dichotomous situation at the bottom right in Figure 2, involving responses scored in two categories, when the person ability is the same as the item difficulty, the odds of a correct or agreeable response are 50-50.

To take another example, in the curves at the upper left in Figure 2, someone with a measurement of about ¬0.5 logits has about a 0.75 likelihood of success at level 1, with a 0.125 likelihood of both failure (0) and greater success (2), and a negligible chance of the highest level of success (3). This person's very low chance of success on the more difficult variation on that task may be of no consequence if the task is irrelevant to the demands of this person's daily life. With further development in this person's abilities, however, the task's relevance increases, and so does the person's ability to successfully address it. At some point around 1.2 logits on the (horizontal) ability scale in the upper left curves in Figure 2, the person's ability to succeed on the easier level 1 version of the task will be just as likely as their ability to succeed on the harder level 2 version. Multiple test, assessment, or survey items, as well as the challenges of everyday life, targeting this level are likely to be answered correctly or rated successful about half the time, which is to say, randomly. The person's location in relation to the two versions of the task is unstable, flipping back and forth between them.

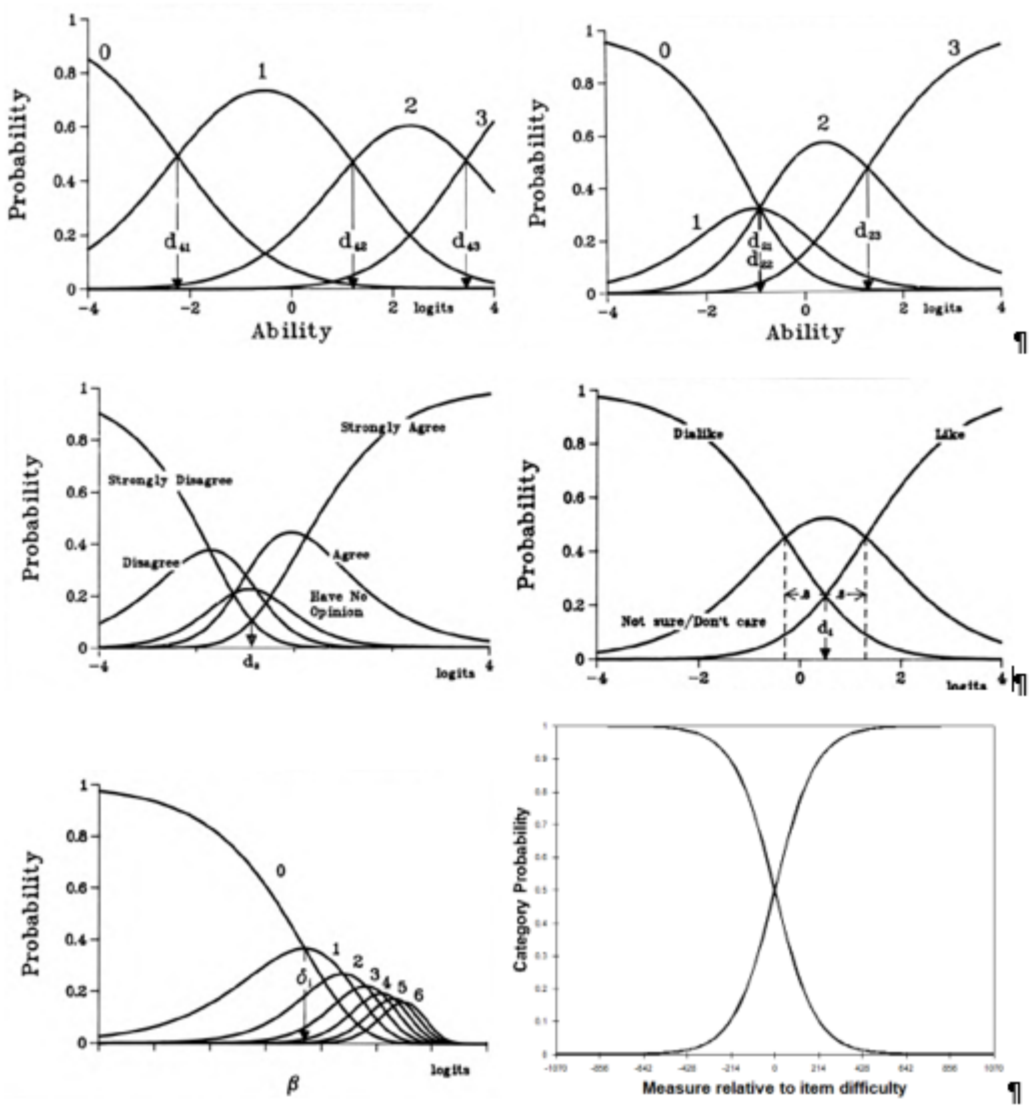

Figure 2. Examples of response category probability (likelihood) curves in measurement theory [264], [278].

This is the level at which the person’s status reaches a bifurcation and is fluctuating. If the existing environment offers clear supports inducing behaviors at the higher order level, a transition to that level becomes more likely than if individuals must create those supports themselves or do without them. This is the situation of “probabilistic epigenesis,” where individual response likelihoods are damped or amplified by interactions between internal capacities and environmental features [88] (pp. 52-53), [279] - [281]. Though analogies between the genotype and the theory of the measured construct, and between the phenotype and the physically material instrument, may be apt, evolving mutability is not a strict function of random fluctuations but depends on the expression of capabilities finding traction in the external environment. Far from being “a simple additive function of gene x environment interactions,” advances in epigenetics and genomics had not coalesced around a core set of principles characteristic of a paradigm in either biology or psychology by 2015 [88] (p. 10), and arguably still have not. Methodical distinctions between probability and likelihood situated in relation to Prigogine’s theory of dissipative structures, models for measurement, and developmental psychology might contribute to the coherence of such a paradigm.

The transition thresholds in Figure 2 could be made analogous to Figure 1’s [188] (p. 30) illustration of the succession of species in the same niche by making the vertical axis in Figure 1 represent likelihoods summing to 1.0 across the curves. The shifts across these ranges of hills occur as the likelihood of one cognitive or biological form of life dominating decreases and that of another increases.

Figure 1 shows each successive curve as higher than the preceding one, but this need not always occur, especially if the characteristics of the ecological niche change. The analogy here is complemented by the way these likelihood functions are akin to resonating clouds of matter, energy, and/or information. The model posits the infinite populations of all possible persons and items participating in the measured construct. The large numbers of actual people and tasks participating in the construct in daily life are sampled in experiments modeling their interactions. This modeling process has the aim of creating tools embodying people's collective rationality in ways useful for defining general paths of least resistance adaptable to individual circumstances. The experimental process replicates real life and simplifies it to an actionable model that can be exported from the laboratory back into the world. Care must be taken to separate and balance the unrealistic ideal of the heuristic fiction posited by the formal law structuring the model in relation to the arbitrary medium of the functional measurement's abstract standard unit and in relation to the chaotic randomness and fluctuations of individuals' concrete data. The model becomes a shared medium for communication to the extent that it is augmented by quality assured traceability, consensus standards, laboratory accreditation, etc. contextualizing the management of individual learning, healing, and growth.

B. Modeling stochastic resonances and the microprocessing of facts

The resonating clouds of stochastically appearing and disappearing data points provide a macroscopic analogue of the Poincaré resonances Prigogine [119] (p. 151) says "measure themselves" by means of their interactions. The explicit, overt measurements made in laboratory research extend the implicit, latent measurements being made in nature, and in society. The models are useful in applications only insofar as they in fact have successfully leveraged their sufficient statistics and identifiability to represent real phenomena. The structures, processes, and outcomes of the real world are encapsulated in laboratory models useful to the extent they can inform decisions and behaviors in everyday life.

When the limiting conditions in which repeatable references to objective facts are understood and have been reproduced often enough in varying circumstances to inspire confident applications, there is no longer any need to continue the "microprocessing" of those facts, and the model can be packaged in an intuitive technology for commercialized export from the laboratory [130] (pp. 143-144), [137] (pp. 132-135). In examples from educational psychology, this process has repeatedly been effectively implemented [52], [53], [254], [257], [258], [282] - [284].

Prigogine argues that Poincaré resonances are modeled via the theory of dissipative structures as objectively repeatable and reproducible phenomena in a way that removes the need for the "mysterious intervention" of an observer at the quantum level [119] (p. 131), [285]. As Prigogine [119] (p. 46) puts it, "Instability driven by resonances plays a fundamental role in changing the formulation of quantum mechanics." Alternative approaches to eliminating the "extravagant role in the evolution of nature" [119] (p. 15) assigned the observer by Bohr's Copenhagen interpretation of the quantum phenomenon are also offered by Bohm's [286] - [300] ontological interpretation and by Wheeler's [301] - [306] sense of a participatory universe. Fuller elaborations of Bohm's explicitly and Wheeler's implicitly Hegelian perspective on these issues are in development.

Instability driven by resonances also played a fundamental role in changing the formulation of social and psychological measurement. These resonances explain why "the stochastic model of Rasch, which might be said to involve weaker assumptions than Guttman uses [in his deterministic models], actually leads to a stronger measurement model" [307] (p. 220). An analogy between the physical phenomenon of stochastic resonance and response process likelihoods in psychological measurement [308] - [310] [311] (pp. 69-71) may be substantiated by dissipative structures' incorporation of Poincaré resonances, which Prigogine [119] (pp. 36, 131) describes as playing a key role in deterministically chaotic nonequilibrium systems [285], [312] - [314].

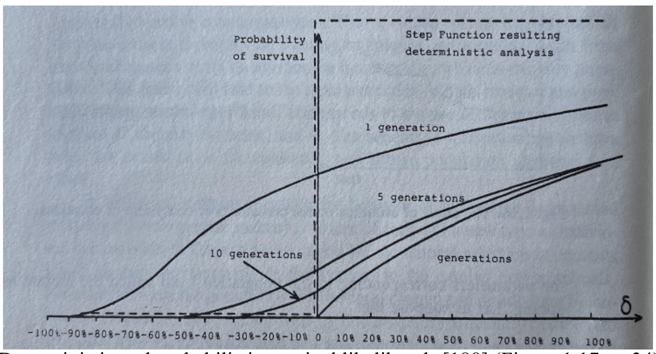

Figure 3. Deterministic and probabilistic survival likelihoods [188] (Figure 1.17, p. 34).

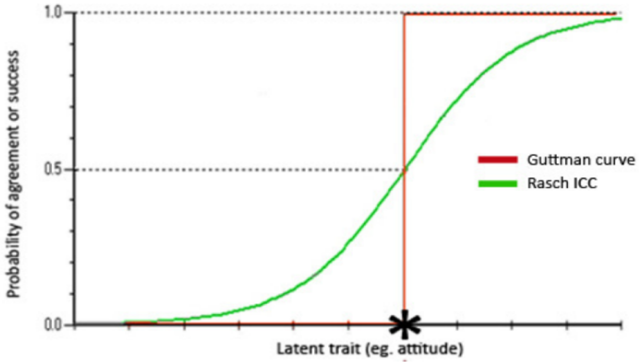

Figure 4. Deterministic Guttman and probabilistic Rasch response functions [337] (p. 253).

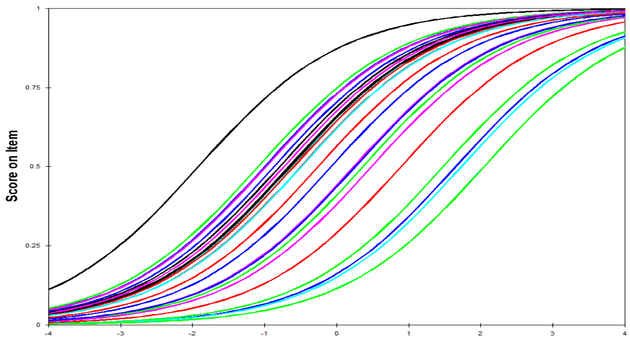

Figure 5. All of a single instrument's item characteristic curves [278].

Prigogine's focus on noise-induced phase transitions is also relevant in the context of measurement modeling for the value obtained for estimation and substantive theorizing from the focus on individual response likelihoods. The gradient of shifting likelihoods is associated with an information function that operates in the etymological root sense of "inform." That is, a strictly deterministic step function of the kind described in Prigogine and Allen's Figure 1.17 and by Guttman's [315] scalogram approach (see Figures 3 and 4) results in an "attenuation paradox" [316] - [318]. The paradox emerges as transitions between levels become more deterministically defined, and more certain, which then diminishes the capacity to estimate the distances between them.

Note that attention to individual response likelihoods in the measurement modeling context contrasts with the statistical modeling approach to the attenuation paradox taken by Lord [319] (pp. 4-5), where "a test score is a sample statistic that is to be used to test some hypothesis." The statistical focus on group-level statistics emphasizes uses of p-values and explained variance in evaluations of the fit of models to data [320], which leads to methods and results paradigmatically opposed to those developed using the measurement focus on individual-level response processes emphasizing meaningful interpretations in evaluations of the fit of data to models [67], [193], [201], [202], [321].

The deterministic structure's vertical step function contrasts with the additional information provided by the smoothly transitioning likelihoods illustrated by the generational survival and item characteristic curves in Figures 3, 4, and 5. Regarding Figure 3, Prigogine and Allen [188] (p. 33) state a model of a probability of surviving long enough on average to reproduce as:

$$P_{\text{surviving to reproduce}} = \delta / 1 + \delta - e^{-\delta / 1 + \delta} \qquad (1)$$

Here, δ is the fractional change in selective advantage offered by a biological mutation, or, extrapolating via Prigogine's analogies, a newly achieved Piagetian level of development, or a social innovation. Expanding δ into two terms capturing both the mutation and the context of its fractional change in selective advantage, and rewriting the equation as a probabilistic conjoint measurement model [61], [282], this becomes:

$$P_{\text{surviving to reproduce}} = e^{(\beta - \delta)} / 1 + e^{(\beta - \delta)} \qquad (2)$$

which gauges reproductive success as a function of the difference between the new form of life's survivability β and the challenges δ posed by the environment. Levels of additional advantages represented by what Prigogine refers to as a "supplementary parameter" can be modeled in the form of:

$$P_{\text{surviving to reproduce}} = e^{(\beta - \delta - \tau)} / 1 + e^{(\beta - \delta - \tau)} \qquad (3)$$

where τ [262] - [264] represents the added difficulty posed by challenges within specific ecosystem niches, or, conversely, the added ability exhibited by a mutation or innovation. In a further expansion:

$$P_{\text{surviving to reproduce}} = e^{(\beta - \delta - \tau - \lambda)} / 1 + e^{(\beta - \delta - \tau - \lambda)} \quad (4)$$

where λ could be another source of added environmental challenges that vary depending on the context, such as a predator or a systematic lack of resources in an ecological niche, a judge rating performances, a multicomponent task, an explanatory scheme predicting item locations, etc. [322] - [329]. Additional model features can be added to address problems of items' or raters' local dependencies, systematic differential item functioning, latent class variations, etc. [330] - [336].

The Socratic midwifery of a fully formed mode of being able to take on a life of its own in an appropriately resourced environment depends, in Prigogine's language, on the size of the fluctuation. In the substantive terms of psychological measurement, it depends on the likelihood of achieving a decisive consolidation in an ability or performance at a sustainable new level. Sustainable cognitive operations and behaviors are functions of uncertainty. At the bifurcation point—the category transition threshold—achievement may fluctuate across tasks posing equivalent challenges with 50-50 odds, randomly. With low numbers (fewer than ten) of opportunities to demonstrate the level of achievement, performances that average to random coin tosses may vary in their individual likelihoods much more widely than those based on larger numbers of observations (30 or more). Either way, successes will default to the more likely, previous level of achievement until a new stability coheres with higher likelihoods and less uncertainty at the new level.

Prigogine and Allen [188] (p. 27) say that in large physicochemical systems there is always one maximum likelihood that is dominant, but this is not the case in sociocognitive systems, as is illustrated at the upper right and middle left in Figure 2. Even in large datasets categorizations may be too finely graded to permit every distinction to have the highest probability (likelihood) within even a narrow range. In addition, an instrument administered to a sample that performs at markedly high or low levels, and so is off target, may have too few responses at the unoccupied extreme to allow estimation of the transition thresholds. This situation raises the problem of calibrating instruments on appropriately chosen samples, and not on samples drawn for experimental or applied purposes. Items included on calibrated instruments should be anchored at standard unit values, not recalibrated to a different unit in every new application. Disagreements as to whether it is reasonable to collapse unobserved, and so disordered, categorical distinctions on the basis of the data, or if they should be retained on the basis of the construct theory, has led to some controversy around the value of categories and their scoring [338] - [342]. Additional issues concern the summing of graded response models' cumulative likelihoods, which are always ordered but which then prevent the inferential separation of item and person parameters [343], [344] (pp. 322-324), [345], [346].

Prigogine and Allen [188] (pp. 26-27) distinguish between stable linear systems exhibiting empirical (phenomenological) proportionality and unstable nonlinear systems far from equilibrium "in which the kinetic equations give rise to bifurcations" and "the identification between these macroscopic equations and the first moment equations may become completely incorrect, as the probability distribution may cease to be sharply peaked." When this kind of a double-humped distribution occurs, the item's error distribution becomes bimodal, rendering the location of the transition threshold on the scale unresolvable [347]. Whether this problem should be resolved by anchoring the thresholds at established values, equating with a previous sample, revising a poorly designed rating scale, or by analytically collapsing categories comprises the substance of the "disordered categories" controversy [338], [339]. In accord with the principle of taking up likelihood-based natural laws and not deductively making do with incomplete information, attention is focused here on the need to establish and maintain substantive commensurability in a shared frame of reference.

In finding equal heights in likelihood distribution maximums, and then tracing the line of coexistence between two solutions on the basis of a stochastic potential, Prigogine and Allen [188] (p. 27) are effectively modeling different categories' response likelihoods so as to link them and make them comparable. This is akin to addressing the problem of instrument commensurability in a form analogous to common sample or common item equating, where the meaning of what counts is connected across contexts [348] - [350]. They are emphatically not taking a phenomenological and empirical approach to statistical modeling in the manner of equipercentile equating, where "sampling fluctuation…is the subject of concern" [351] (p. 165). Here, numeric statistics that may be devoid of meaning are made comparable only in terms of their relative proportions.

Summarizing, both measurement theory's focus on stochastic invariance and Prigogine's sense of deterministic chaos can be seen as:

- distinguishing deductive population statistics motivated by sampling problems from inductive individual level observations motivated by the response process;
- contrasting likelihood and deterministic step functions describing an innovation's potential for surviving a varying number of generations; and
- modeling evolutionary sequences of biological or sociocognitive species inhabiting the same or varying environmental niches.

Measurement theory and the theory of dissipative structures differ in the rigor with which they conceive and implement the distinction between sampling probabilities and response likelihoods. Prigogine and his followers tend to remain methodologically locked into a statistical, analytic perspective. That is, with no concept of the need for and possibility of calibrating instruments embodying the laboratory model in real world applications, the idea of enacting the research results on broad scales in ways capable of mediating theoretical ideals and unique local circumstances is never brought up. Attention turns now to what this might entail.

IV. Prigogine's "Trinomial Conjecture," Semiotics, and Measurement in Practice

De Castro and McShea [25] (p. 3), referencing what is here shown as Figure 6, say that, in positing a "trinomial conjecture," Prigogine asserted that:

> *…all complex dissipative structures, ranging from the classic 'Bénard instability' … to organisms and human societies, [share a] common basis in the fluctuation–function–structure trinomial (Fig. 1). Prigogine thought of the trinomial as a bridge uniting the sciences, uniting the physical with the biological, social, and human.*

With no mention of Prigogine's trinomial, Bailey's [3] (pp. 20-28) social entropy theory points out the importance of adding a mediating third indicator term in two-level sociological models referencing only conceptual and empirical contrasts (Figure 7). In accord with Prigogine, however, Bailey explains that the levels are discontinuous and cannot be reduced in the manner of a numeric hierarchy, where higher level aggregates are the sums of the lower-level parts.

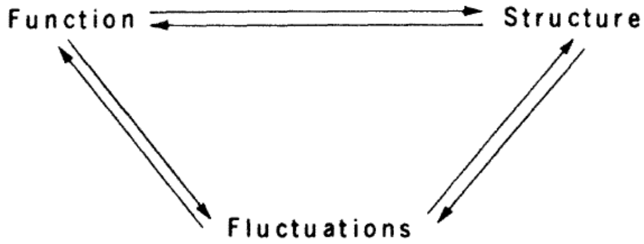

Figure 6. The "trinomial conjecture" (unnumbered figure from [16] (p. 120), [352] (p. 781)

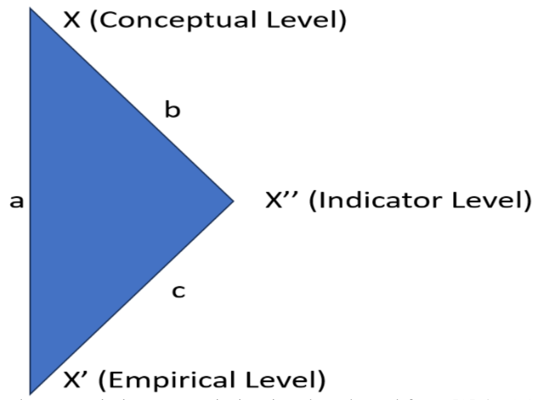

Figure 7. Social entropy theory variation on semiotic triangle, adapted from [3] (p. 26, Figure 2.1).

Bailey's semiotic distinctions between ideas, words, and things effectively generalizes the three terms in Prigogine's trinomial, where, within open systems, physical structures perform functions that may fluctuate, varying in ways that may dissipate entropy in the direction of increasing order and complexity. Bailey points out that, linguistically, structure is provided by conceptual ideals; function is embodied in semantic, alphabetic, and phonemic indicators; and fluctuations occur in relation to the empirical things represented. Brooks and Wiley [11] extending the semiotic analogy, see biological systems as self-referential, where structure corresponds with the genotype, function with the phenotype, and fluctuations with mutability [353]. In nature, each species forms a system integrating structural genotypes, functional phenotypes, and fluctuating mutability. In human affairs, analogously, each social form of life forms a system integrating formal conceptual structures, abstract media, and concrete local circumstances.

Further extending the analogy, we can see that, in human psychology, the superego structures conscientiousness and identity, while the id functions to embody subjective understanding, and the ego manages fluctuating daily events with varying effectiveness. In governance, constitutional law, rights, and the judiciary correspond with structure, while legislative measures and proportionate representation correspond with function, and executive administration, with mutable fluctuations. In science, theory and axioms structure formal laws, metrological unit standards and calibrated instruments function as abstract media, and experimental data fluctuate to reveal anomalous opportunities for new learning.

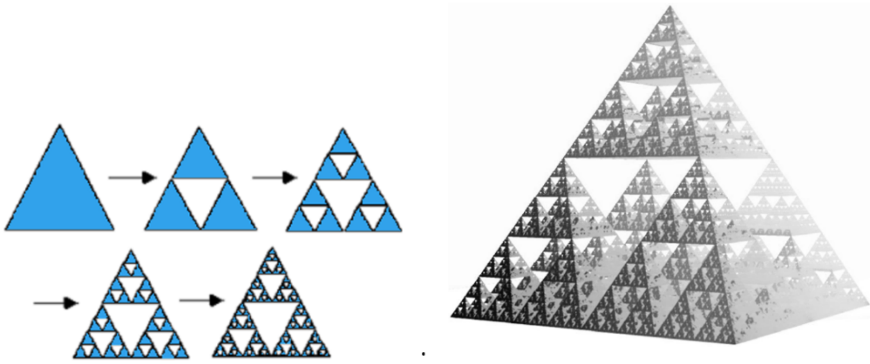

Figure 8. Sierpinski triangles and pyramid [355]

These analogical correspondences with the semantic triangle bring out the general relevance of semiotics as a model spanning the full range of fields, from physics to psychology [122] - [129], [353]. The fractally repeating pattern of Prigogine's trinomial across domains is aptly illustrated by the Sierpinski triangle or pyramid (Figure 8), a geometrical gasket that retains its properties of infinite area or volume at any level of magnification. This property of mathematically proportionate infinite area and depth is referred to as "scale-free" for reasons of its invariance but needs to be distinguished from the properties of measurement models capable of structuring consistent inferences across instruments, which also sometimes are referred to as "scale-free" [354]. The real-world relations of each set of triples across domains will surely distort the idealized images shown in Figure 8, but the illustration nonetheless aids in intuitively grasping the chaotic depth and breadth of the interpenetrating interdependent orders involved.

Dating from the 1867-1914 contributions of Peirce [356], and more recent efforts by Sebeok [129], [357], [358], a transdisciplinary semiotic theory of self-organizing systems integrates objective factuality and subjective meaning in a nondualistic worldview and approach to science [122] - [128], [353]. The expansion of semiotics from its original linguistic focus to broader applicability as a theory of evolving life in biosemiotics and ecosemiotics, and of information in cybersemiotics, has led to recognition of the need for its systematic operationalization in distributed cognitive ecologies' conceptual infrastructures:

> *A combination of cybernetic, systemic and semiotic understandings of the semiotics of information, cognition and communication area seems therefore crucial to the development of a systemic Cybersemiotics that can support teaching and human development* [124] (p. 20).

Philosophical investigations of meaning in science and measurement have developed corresponding theories of how spoken and written language serve as vehicles of thought [72], [81], [82], [120], [121], [130], [131], [135] - [137], [142], [359] - [362], and these are applied in psychology and social science as means of implementing nonreductive methods [108], [109], [311], [363] - [368]. Developmental psychology [87], [88], [90], [91], [95], [96], [369] has, in addition, independently developed self-referential theories of meaning and qualia toward analogous ends.

These initially separate trends have converged in research showing that stable psychological states and unstable transitions between them exhibit stage-level developmental structures, where measurement scaling research shows the existence of consistently separated discontinuous ranges [96], [156], [172], [246], [248] - [250], [370]. Fluctuations in this context occur in the process by which conceptual and/or behavioral integrations coordinate and align previously unarticulated background assumptions, making them objects of operations. Educators have then come to focus on facilitating learning as benefiting from environments in which playful experimentation is supported, misconceptions are elucidated by regular, actionable feedback, and failure is recast as the best way to improve outcomes [95], [97], [99], [156]. More will be said on this below.

Falmagne and Doignon [371] (p. 135) provide an explanation of the evolution of rationality from naivete to sophistication, formalized by a stochastic process with three interlinked parts that correspond with Prigogine's trinomial conjecture:

- Fluctuations: "One [part] is a Poisson process governing the times t1; t2; …; tn; ... of occurrence of quantum events of information, called tokens, which are delivered by the medium."
- Function: "The second [part] is a probability distribution on the collection of all possible tokens, which regulates the nature of the quantum event occurring at time n. "
    - "Any token is formalized by some pair xy of distinct alternatives, bearing a positive or negative tag. "
    - "The occurrence of a positive token xy signals a quantum superiority of x over y, while the corresponding negative token y indicates the absence of such a superiority."

- Structure: "The last part of the stochastic process is a Markov process describing the changes of states occurring in the subject as a result of the occurrence of particular tokens."

Similar ways of conceptualizing shifts across levels of complexity are described in the measurement perspectives presented in Wilson's [248], [250], [372] Saltus model, Commons' [373] model of hierarchical complexity, and K. Fischer's [94], [95] skill theory. In each case, concrete fluctuations in empirical experience coalesce into repeating abstract patterns akin to the schooling, swarming, or flocking behaviors of fish, insects, or birds, as illustrated in Ireland and Statsenko [374] (p. 96, Figure 2). The coherence of these patterns induces analogical and metaphorical associations at the formal, structural level of complexity when new experiences can be related to previous ones. Gaining a clue, hint, or hunch of a salient source of value to anticipate and look for in the world makes it possible for a descending dialectic to proceed by naming the abstract pattern via a metaphor, sharing it in communications, and applying it in new, previously unmet instances of the experience to negotiate shared understandings with others.

V. Informational Entropy vs Thermodynamic Entropy in Measurement

There are enormous variations in the explicit and implicit meanings and mathematics associated with both entropy and information, so many, in fact, that sorting them all out seems an interminable task [29] (pp. 9-11). Though it will be impossible to fully achieve, I would like here to try to not contribute to additional confusion. To begin, although the definition of entropy as a fixed amount of information in communications theory since Shannon is formally analogous to Boltzmann's thermodynamic entropy function, there are important reasons for recognizing and actively distinguishing between them. Shannon and Weaver defined the measurement of information in terms of a discrete probability distribution P where the entropy H of P is given in a log base two function termed bits. The entropy H of P attains its maximum value of log base 2 of the sample size n when P is equally probable across the entire range of the distribution. The quantity of information needed to decide between two equally probable possibilities is termed a bit, and the number of bits required to obtain a complete statistical description of a system determines its overall information content.

In Shannon's [375] (pp. 50-57) sense, a message's information content, then, is equal to its entropy in the sense that the most informative string of symbols of a given length will be random, where each symbol is equally probable. Redundancy and exceptions, in contrast, create divergent differences in symbol probabilities, as each is no longer equally unique. Shannon information content and entropy are then reducible in ways that are not always interpretable physically [11] (p. 65), leading to Haynes et al.'s [1] suggestion that mature applications of entropy in psychology and the social sciences should eschew connections with thermodynamics.

An opposite definition of the relation of entropy and information is given by Layzer [376], who sees them as inversely constrained by a simple conservation law holding that their sum is constant and must be equal to the maximum possible in a given situation. Now, in Layzer's sense, entropy decreases as complexity and information increase, so that evolution becomes aligned with the latter in the context of evolving dissipative structures. This does not, however, change the overall characterization of the statistical sense of probability employed. Shannon's statistical sampling perspective on the content internal to messages defines maximum information content mechanically, so the whole is the sum of the parts. There is no distinction between levels of complexity.

No mention is made of semantic closure [353] or of the receiver's semantic reaction [377], [378], which involve the capacity for the content to inform meaningful inferences, interpretations, or actions outside of the communications channel. Though Weaver [379] (pp. 25-28) raises these issues, he minimizes their importance, saying they likely imply only "minor additions, and no real revision" (p. 26). Weaver unabashedly accepts that "the concept of information developed in this theory…has nothing to do with meaning, and…deals not with a single message but rather with the statistical character of a whole ensemble of messages" (p. 27). The focus on information content is then entirely external to the communication. Unexpected intrusions of surprising and improbable symbols, or of emphatic repetitions of urgently important symbols, reduce information and entropy in a mechanically dynamic way in this statistical perspective even though they may represent essential features of the environment demanding close attention. Information so defined is, however, incapable of representing itself recursively, and so sets up closed systems incapable of evolving.

A measurement modeling perspective on recursive processes [246], [249], [250], [369], and on fractal, chaotic processes [380], [381], in contrast, focuses on irreducible variation in the contributions of each symbol and each message to an overall composite meaning that is greater than the sum of the parts. Now, information is defined in terms of the sufficiency of consistent, repeatable, monotonic likelihood functions. These likelihoods stochastically fluctuate within semantically closed loops structured in the flows of open systems, just as matter and energy do.

VI. Practical Implications of Entropy-Dissipating Multi-Level Complexity

More specific points of contact between the nonequilibrium thermodynamics of entropy-dissipating processes and social processes then involve ways in which Prigogine's sense of a new dialogue of humanity with nature implies:

- the objective repeatability of structures Prigogine describes in terms of self-organized "deterministic chaos" and which measurement theory postulates in terms of reproducible patterns of stochastic invariance that demonstrably maintain their properties across samples, observers, and instruments [348], [382] - [390];
- the shift Prigogine sees away from a sense of probabilistic models connoting a resigned acceptance of incompleteness and ignorance toward probabilities that are foundational expressions of scientific laws, which aligns with measurement theory's perspective on differences between deductive population-level probabilistic models motivated by sampling issues and inductive individual-level likelihood models motivated by the response processes generating the data;
- physical processes occurring at the quantum level that Prigogine and others suggest inform an objective ontology that removes the need for an observer to play an "extravagant" role in the evolution of nature, and which accords with developments in the domain of semiotics concerning the ways in which physical, biological, and information processes can be seen to read, write, and measure themselves; and
- violations of the traditional binary logic of the law of the excluded middle and the law of noncontradiction, which resonate not only with measurement theory but also with parallels in the multivalued, nonternary logics posited in aesthetics, ethics, existentialism, hermeneutic phenomenology, and feminism; further research in this regard is in process.

The implications of this new dialogue with nature for new dialogues among humans suggest a pragmatic and actionable program for advancing political economies explicitly intended to take the form of participatory social ecologies. Such ecologies, like those in nature, involve micro, meso, and macro forms of life exhibiting within-individual, individual, and population nonequilibrium processes. These levels of complexity are currently inconsistently recognized in widely institutionalized information systems that sometimes rightly distinguish between, for instance, numeric counts of rocks and measured quantities of rock, while also not distinguishing between numeric counts of correct answers or points of agreement, and measured quantities of abilities or attitudes [391] - [393].

Though current organizational systems persistently confuse and fail to separate these levels into distinct but interrelated domains, calls for consistently achievable models and methods for doing so date back several decades [394] - [399]. Hayman et al. [396] (p. 31), for instance, say:

> *Our hypothesis is that: The utility of a set of evaluation data varies inversely with the number of organizational levels between the action the data describe and the decision process they are intended to influence.*
>
> *In other words, the closer a set of data is to the organizational level for which it will be used (for decision-making), the more useful the data will be…. Conversely, the principle states that the further a set of data is from the organizational level for which it will be used (for decision-making), the less useful that data will be.*

According to this hypothesis, then, because of the great distances separating fragmented and incommensurate local data systems from the global decision processes they are intended to influence, efforts like the United Nations Sustainable Development Goals and the Carbon Disclosure Project must inevitably fail. Worldwide science and commerce conducted in the mathematical language of the SI units has succeeded on huge scales, altering its environment and thereby compromising its potential for continued productivity. Global systems are causing human suffering, social discontent, and environmental degradation that will be successfully addressed only when approached at the relevant organizational level. These problems will be made tractable only when, in the manner of a Chinese finger puzzle, humanity ceases applying the reductionist and dualistic top-down, outside-in methods causing the problems and relaxes into the nondualism of a new class of SI units embodying metrological solutions distributing irreducibly complex unified subject-object technologies globally [110], [400] - [404]. Prigogine's thesis of a "new intelligibility" and a new science of collective rationality provides conceptual tools and perspectives essential to meeting 21st-century challenges at a level offering viable possibilities for their solution.

Rousseau [399] also takes up the ecological fallacy and the organizational problems that follow when individual relationships are over-generalized, and issues of level are not considered in design as well as in data aggregation. In Star and Ruhleder's [405] (p. 118) terms:

> *If we, in large-scale information systems implementation, design messaging systems blind to the discontinuous nature of the different levels of context, we end up with organizations which are split and confused, systems which are unused or circumvented, and a set of circumstances of our own creation which more deeply impress disparities on the organizational landscape.*

Ireland and Statsenko [374] expand on the theme by providing extensive breakdowns of the organizational implications of complex systems theory. Though they do so in the usual manner that assumes centralized planning and data analysis to be the only available options for policy and programs, a point of departure toward metrological models of distributed cognitive ecosystems is suggested by their recognition of the fractal nature of project management and the relevance of mathematical power laws [374] (p. 95). They illustrate the fractal parsing of project responsibilities and processes using a Sierpinski triangle, though it is not named as such, and they helpfully state the problems discontinuous demands on modeling impose by having to address both the entire organization's needs as well as individual decisions and behaviors.

Multilevel log-interval measurement models are in fact instantiations of the kinds of power laws referenced by Ireland and Statsenko. Their applicability to problems of organizational complexity are further suggested by Ostrom [406] (p. 50), who argues that:

> *The rules affecting operational choice are made within a set of collective-choice rules that are themselves made within a set of constitutional-choice rules. The constitutional-choice rules for a micro-setting are affected by collective-choice and constitutional-choice rules for larger jurisdictions.*

Scott [40] shows that the history of humanity's autocrats and despots demonstrates just how far reductionist higher order constitutional- and collective-choice rules can be invented and imposed to serve the interests of an elite at the expense of the greater good. He [40] (pp. 355-357) suggests, without mentioning semiotics by name, that an alternative nonreductionist approach could be formulated by taking language as a model, so that the emergent, self-organized sociohistorical processes by which meaningful things are brought into words comprise the basis of policies and programs.

That kind of a possibility for operationalizing Ostrom's distinctions between organizational levels is then apparent in Hayek's [116] (p. 88), [117] goal of enabling people to do the desirable thing without having to be told. Meaningful freedom of choice constrained within the limits of a sociocognitive ecological niche might be hypothesized to follow from operational choices induced by naturally cohering, self-organized collective choice rules, which in turn are induced by constitutional choice rules that can similarly be shown to assert an independent, repeatable and reproducible existence.

A parallel process can be seen in Piaget's [86] emphasis on the importance of play in learning and development as how children's capacities are induced in relation to the learning environment across preoperational, concrete, and abstract levels of complexity. Nersessian's [92] sense of scientific experimentation as play works toward a common end and substantiates Dewey's [407] (p. 201) characterization of schools as laboratories for experimenting with life. Fleshing out these parallels, we can see that, in Gadamer's [89] (pp. 104, 367), [366] terms, answers to questions in dialogue are operational choices playfully induced by collective choice rules represented in the available grammatical and phonemic standards; these latter are themselves induced by the conceptual determinations structuring them as constitutional choice rules.

Integrating R. Fisher's [189], [190] and Rasch's [63], [65], [210] terms for Ostrom's level distinctions, operational choices are response likelihoods induced by the collectively coherent differences between people's, objects', or processes' abilities or capacities and the difficulties or obstacles they confront. The collectively structured rationality of the construct measured—a learning progression, developmental sequence, or healing trajectory—is then induced by constitutional choice rules demonstrably established by explanatory models [43], [44], [250], [255], [265], [326], [369], [408] - [419] predicting item calibrations and person measurements from their characteristics.

Educational, health care, professional certification, and other systems integrating all three of these levels to various degrees have existed for decades [234], [256], [420], [421], but metasystematic and paradigmatic integrations [52], [53], [254], [255], [258], [283], [422] have scarcely begun.

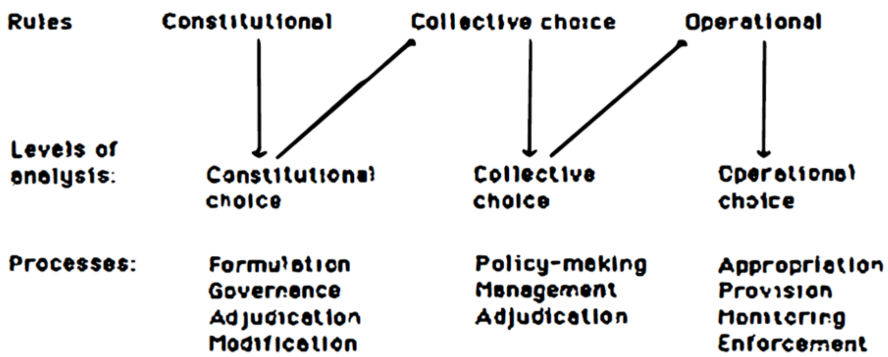

Figure 9. Linkages among rules and levels of analysis [397] (Figure 2.2, p. 52)

Figures 9 and 10, from Kiser and Ostrom [397], [406] illustrate linkages across levels of analysis, where operational choice rules are embedded within collective choice rules, and both are situated in the context of constitutional choice rules. The challenge is to design data, information, and knowledge systems with close attention to the distinct analytic and reporting needs of each level vis a vis the creation of common languages capable of embodying and mediating:

- constitutional choice rules involving the formulation and modification of conceptual ideals explaining and predicting governance and adjudication decisions and behaviors;
- collective choice rules informing standards for policy-making and managerial adjudications; and
- operational choice rules addressing empirical appropriations, provisions, monitoring, and enforcement.

Semiotically modeled decisions systematically integrate probabilistic forms of knowledge across an irreducible array of discontinuous levels of complexity. They can do so in the context of probabilistic laws of human nature by attending to the interdependencies of the three levels of complexity [423]:

- constitutionally via conceptual maps of measured constructs aiding in the design of measuring instruments justified by explanatory theory demonstrating in a publicly reproducible way a transparent understanding of the object of the conversation [424], [425];
- collectively via standardized Wright maps of the locations of persons and items on the quantitative continuum expressed in the medium of a publicly available common language and metric read from a calibrated instrument, with associated uncertainty and data quality statements [235], [415]; and
- operationally via response maps of the empirical evidence of individual responses useful in guiding instruction, clinical care, management, etc. [426] - [428].

Figure 10 illustrates the involvement of both formal and informal collective choice arenas in operational rules in use. In well-designed systems, (a) local operational decisions concerning the unique situations of individuals will be afforded opportunities for adaptive accommodations lacking in less well-designed systems, with clearly stated tolerances for uncertainties; and (b) formal collective decisions concerning accountable regulatory matters will incorporate uncertainty estimates useful in determining the probabilities of distinct problems in conformity or compliance [56].

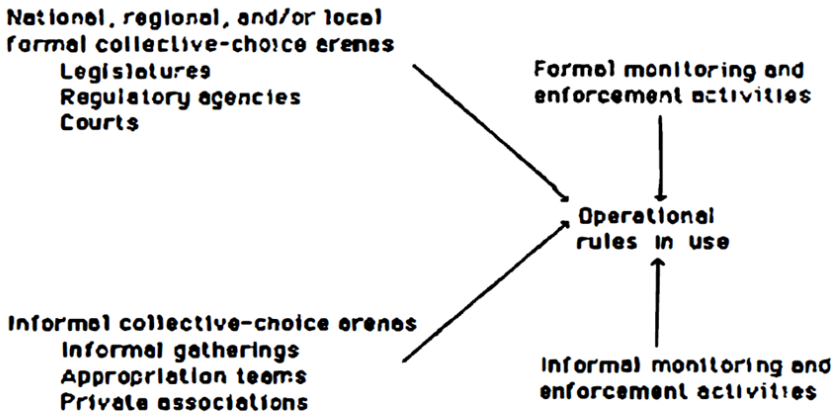

Figure 10. Relationships of formal and informal collective-choice arenas and common pool resource operational rules [397] (Figure 2.3, p. 53)

In this context, in contrast to the compulsory red tape of bureaucracies focused on rigid compliance with sometimes irrelevant policies and procedures, information quality can be fit to the needs of the moment. This can be accomplished by supporting the decision process with information sufficient to the task, which need be neither overly precise or imprecise. Explicitly incorporating uncertainty into the foundations of the definition of knowledge demands estimating it as a factor impacting decisions and behaviors in formal, high-stakes situations. When a fit-for-purpose degree of uncertainty supports the assertion of a decision, that outcome ought to be made scientifically, legally, and financially defensible and accountable, so far as possible.

The importance of distinguishing levels of analysis is plainly key to the reasons why Ostrom's and Star's ideas have been combined in work on infrastructuring participatory social ecologies [429] - [431], though few or no overt references are made in that literature to developmental levels of hierarchical complexity or to metrologically relevant measurement modeling.

VII. CONCLUSIONS

Measurement systems that incorporate "the collective dimension of individual actions" as prescribed by Prigogine and Allen [188] (p. 37) do so by modeling individual responses projecting stochastic invariances at higher orders of complexity. Fluctuations in response likelihood may cohere and exhibit instabilities leading to the emergence of self-organized orderly patterns. These patterns are inaccessible to what Prigogine calls the "collective utility function" of a deterministic expectation of simple static systems. They have, however, long informed practical applications in the meaningful structuring of measurements reliably connecting persistently reproducible invariances with defined metrics in common languages addressing different communities of research and practice in their own terms at their own operational, collective, and constitutional levels of complexity.

Prigogine's proposal that all far-from-equilibrium processes are characterized by evolutionary capabilities realized by the interactions of structures, functions, and fluctuations is supported by the identification of analogous three-part conceptualizations of interacting levels of complexity in multiple other fields. Prigogine's mathematical formulation of probabilistically structured natural laws distinct from deductive statistical descriptions of population dynamics enables a principled engagement with his expectation that his theory of dissipative structures should be relevant to Piaget's theory of cognitive development. The extension of Piaget's account of developmental levels in the model of hierarchical complexity fleshes out Prigogine's theory to the extent that the mathematical terms of the models informing log-interval scales for the measurement of cognitive development generalize the fractal repetition of the evolving structures.

One further emphatic stress on a key consequence of irreducible complexity must be made, given the intention of here of provoking a clear grasp of the implications of a shift from a dualistic and reductionistic conception of the intelligence of isolated individuals toward a nondualistic collective rationality projected at a higher order level. What is emerging from these considerations is a rearticulation of subjective experience, an expansion on the philosophical critique of subjectivity that has been underway for centuries [432], [433]. The intention to complement today's predominant orientation toward a deductive sense of sampling probabilities with a new emphasis on inductive response likelihoods requires a shift away from a conception of subjectivity as alienated from and adapting to an independent objective reality toward a sense of subjectivity as being objectively induced by its constitutive interrelationships with its environment.

A basic manifestation of that interrelationship infuses a fundamental assumption permeating many conceptions of logic and rationality: that explicit conscious control of cognitive operations is a hallmark of science and reason. The force of the cultural environment as a factor shaping the content and limits of individual thinking is truly profound, ironically extending even to the point of making individual's isolated mental operations seem to comprise the essence of cognition. Bateson [102] (p. 145) reports that,

> *Freud, even, is said to have said, 'Where id was, there ego shall be,' as though such an increase in conscious knowledge and control would be both possible and, of course, an improvement. This view is the product of an almost totally distorted epistemology and a totally distorted view of what sort of thing a man, or any other organism, is.*

Diametrically opposed to this view is the common experience of learning how to perform a wide variety of physical and cognitive processes so well that they become intuitive. The "automaticity" of this kind of learning is a well-recognized goal in education [434], [435]. Learning to execute a triple axel, to dance the frug, to pitch a strike, to play the cello, or to wash the dishes do not involve conscious calculations of force, mass, and acceleration that are then mechanically applied to move the body. As Samuel Butler put it, "...the better an organism 'knows' something, the less conscious it becomes of its knowledge" [102] (p. 138).

Contrary, then, to Kahneman's [436] urge for us to think more slowly and carefully, to Rose's [437] and Nadler and Shapiro's [438] strategies for replacing bad thinking with good, and to Stengers' [439] call for "slow science," stands Hayek's [440] (p. 88} concurrence with Whitehead's [441] (p. 61) observation that:

> *It is a profoundly erroneous truism, repeated by all copy-books and by eminent people when they are making speeches, that we should cultivate the habit of thinking of what we are doing. The precise opposite is the case. Civilization advances by extending the number of important operations which we can perform without thinking about them.*

Languages and technologies facilitate the performance of operations we do not understand—such as when reading a thermometer requires no grasp of thermodynamics—by providing a medium objectively extending—inducing—the subjective, embodied experience of a phenomenon [74], [78], [442], [443]. In the same way that a blind person extends the perceptual reach of their senses by using a cane, so also do overlearned musical scales allow jazz artists to collaboratively create intuited improvisations [444]. Everyday language is also overlearned to the point of enabling fluency: the automatic, involuntary associations that flow so quickly that it is virtually impossible to apprehend them before they are made. Oral language is learned physically in terms of the resonances of sounds in the body and the rhythmic inhalations and exhalations of air; we skip over too quickly the importance of the embodied intuitions developed in language use as they provide important clues as to how understanding develops relationally [445].

Just as children form new concepts via complex interactions in physical experience that lead to capacities for the "fast thinking" Kahneman [436] would like to slow down, so also are similar processes systematically cultivated in science. As Prigogine noted, thermodynamics, after all, "was formulated not by the theoreticians of mechanics who contemplate the world, but by the engineers and physical chemists who deal with the world through their experiments" [17] (p. 245).

This perceptive observation is supported by the historical evidence, and may have been prompted by Prigogine's colleague, Stengers, a noted philosopher of science [42], [439], [446]. Kuhn [222] (p. 90), for instance, points out that, of the nine researchers contributing to the quantification of energy conversion processes, seven "were either trained as engineers or were working directly on engines." As was also described by Nersessian [92], the importance of working in close proximity with technologies enabling repeatable experiences in reproducing and exploring controlled effects led de Solla Price [447] (p. 240) to similarly remark that "thermodynamics owes far more to the steam engine than ever the steam engine owed to thermodynamics," and that "historically the arrow of causality is largely from the technology to the science." This historical and ontological priority of technology over science motivates the emergence of the concept of technoscience taken up in science and technology studies

[81], [106], [137], [448], [449]. But the effect of success in advancing the science has been to make the objectively repeatable automatic associations methodically built into tools, standards, textbooks, and professional associations into media for virally communicated social contagions in which the map is mistaken for the territory and the individual mental model for the shared collective rationality.

Thinking, then, as a process of conscious, creative, original, reasoned deliberation is quite rare, because rationality is bound and defined by the limits of the automatic associations facilitated by language [450]. What Kahneman [451] (p. 1450) calls "effortless associative thinking" in bounded rationality corresponds with

- Gadamer's [89] (p. 463) assertion that it is truer to say language speaks us than vice versa;
- Wittgenstein's [452] (p. 74), [453] recognition that "the limits of my language mean the limits of my world;" and with
- Mach's [454] (pp. 481-495) [455] - [457] sense of an economy of thought in which the shared symbol system lowers communications' transaction costs.

Distinguishing the poetics of creative invention from methodical reproductions of proven results, Heidegger [458] (p. 135) accordingly notes that "science itself does not think," meaning that the routine practice of laboratory science takes place in terms that certainly differ across experimental, metrological, and theoretical communities of practice, but which accept the need to operate within well-defined conceptual borders. This state of affairs accounts for Latour's [106] (pp. 249-250) assertion that growing new sciences entail expanding metrological networks; as he [71] (p. 210) put it, "Through the materiality of the language tools, words finally carry worlds."

The same principle applies in the way economic expansions often entail the lower transaction costs afforded by currency unions and metric standards [459]. And Wittgenstein [460] (p. 47) then defines philosophy as a constant battle against bewitchment by language. But instead of struggling against the subjective play of language games contingent on the existing semiotic complex of ideas, words, and things, should not it be possible to imagine other semiotic complexes in which the games played are less viciously circular, self-destructive, and self-defeating?

The opportunities opened up by the implications for practice explored in this essay suggest that there are ample reasons justifying the reconception of the problem as one of learning to free ourselves by relaxing into the finger puzzle trap. The low transaction costs afforded by the availability of premade idea-word-thing associations create an economy of thought from which it is incredibly difficult to leave. New ideas expressed in new words in relation to unfamiliar things rarely are amplified into wide circulation. To do so, they must represent a clear adaptive advantage—perhaps to an environment inducing unsustainable strategies—offering greater economic, social, or other efficiencies, efficiencies which must be broadly understood in not just logical terms but in terms of emotions, politics, aesthetics, and ethics, as well. In contrast to the prevailing view that humans rationally evaluate situations so as to act in their own self-interest, what actually happens is better described in terms of bounded rationality, where behaviors are imitated and analogies are propagated through social networks structured to facilitate virally communicable contagions of meaning and care, many of which may sacrifice long term survivability in favor of getting through the day [13], [31], [461] - [463].

To say the least, a large array of further questions stands in need of further research. Is a nonreductionist model of the structure, functions, and fluctuations of evolutionary change across physical, chemical, biological, psychological, social, and economic domains possible? Can a science of entropically-driven evolving processes occurring far from thermodynamic equilibrium be conceived and implemented at a cross-paradigmatic level of complexity? Such a science would have to be able to supplant the mechanically conceived theory, instruments, and data of the contemporary Western, Cartesian, dualistic paradigm with those of an emerging global nondualistic paradigm. Each domain would have to be energized by the physical work performed by dissipated entropy production in each sphere's interacting structures, functions, and fluctuations. Order-of-magnitude shifts in the efficiencies of entropy dissipation would be induced by the infrastructure of each newly emergent level of complexity integrating the previous level's operations with enhanced dissipative opportunities afforded by the external environment.

In accord with that model, in the emerging paradigm, metasystematic paradoxes of heterogeneously unified and disunified, harmonious and dissonant, voluntary and involuntary individual operations would have to be integrated into shared symbol systems powering language as the vehicle of thought. The kinds of questions emerging here include but are not limited to the following:

- Might we finally be on the verge of productively fulfilling Bohr's expectation that, having encountered a paradox, there is some hope of progress [464] (p. 140), [301] (p. 686)?
- Might R. Fisher's [189], [190] distinction between deductive population-level probabilities and inductive individual-level likelihoods, and Rasch's incorporation of the structure of natural law in his models of individual-level measurements, be combined to create an entropy-based SI unit defining a scaling factor analogue of Boltzmann's constant in information theory, which today remains just as unavailable as it was in 1959, when von Foerster [36] (p. 19) lamented its absence?
- Restating that question, can shared languages and common metrics calibrated as representations of simultaneously global generalities and local specificities be operationalized as the nonequilibrium

thermodynamic engines energizing labor-saving processes and lifting the burden of initiation in an economy of thought?

- Might the dissipation of entropy inform the coherence of a new class of SI units in a manner analogous to the way the speed of light does for the existing SI?
- In other words, how might Prigogine's sense of a new intelligibility inform or contrast with the new science of enchantment anticipated by Sahlins [465], or the evolving participatory complexity described by many others [30], [33], [301] - [304], [436], [466]?
- Will humanity find ways of operationalizing nonWestern and premodern traditions in a new paradigm that relinquishes dualistic reductions to isolated individuals in favor of cybernetic feedback loops in mutually causal, interdependent relationships?
- Can the similarity of the logical-mathematical structures common to nonequilibrium processes across physics, biology, and psychology inform a new paradigm transforming the thermodynamic "metrisation of the economic state space" begun by von Neumann, Leontief, and others [9], [467] - [469]?
- Can we imagine how models of collective rationality might be embedded in the rules, roles, and responsibilities of a new institutional economics of human, social, and natural capital?
- Can humanity learn to think globally together at the same time it acts locally as uniquely situated individuals?
- Can the seemingly irresistible cultural power of the dominant paradigm's categorical reductions be circumvented in ways that enable the organic cultivation of a new paradigm of irreducible complexity?
- Might this be facilitated by shifting the theory of games in economics away from centrally planned analytics and assumptions of hyperrational consumers toward a more authentic sense of play truer to the distributed participation of players whose undivided attention is caught up in the flow of events?
- Can the inherent insufficiency of systematically fragmented solutions applied to global problems be recognized and addressed in time to prevent clearly impending climate disasters?
- Might individuals be empowered to profitably innovate new social technologies on mass scales by new institutional economies, successfully addressing global problems at the global scale where they exist?
- Will the long-sought goal of reducing all sciences to physics be accomplished, ironically, not only by means of irreducible complexity but also by constituting the identity of each science as an independent domain of investigation?
- Might governance become an instrumentally mediated integration of art and science, like music?

Questions in this vein take up the general applicability of a semiotic model of hierarchical complexity as a matter in need of close attention. Could a coherent system of entropy-based metrological unit standards feasibly structure communications and lower transaction costs in a multilevel ecological economy of human, social, and natural capital markets? The challenges humanity faces in moving toward needed solutions are immense; but having formulated the problem, human ingenuity may yet win the day.

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[1] Haynes, K. E., Phillips, F., Yu, M. C. Y. Recent applications of entropy in social and environmental sciences. In *Handbook on Entropy, Complexity and Spatial Dynamics;* Reggiani, A., Schintler, L. A., Czamanski, D., Patuelli, R., Eds.; Edward Elgar Publishing, Northampton, Massachusetts, USA, 2021; pp. 32-45.

[2] Georgescu-Roegen, N. *The entropy law and the economic process.* Harvard University Press: Cambridge, MA, USA, 1971.

[3] Bailey, K. D. *Social entropy theory*. State University of New York Press: Albany, NY, USA, 1990.

[4] Binswanger, M. From microscopic to macroscopic theories: Entropic aspects of ecological and economic processes. *Ecological Economics*, **1993**, *8*, 209-233.

[5] Floyd, J. Thermodynamics, entropy and disorder in futures studies. *Futures*, **2007**, *39*, 1029-1044.

[6] Mayumi, K.; Giampietro, M. Entropy in ecological economics. In *Modeling in ecological economics*. Edward Elgar, Cheltenham UK, 2004, 80-101.

[7] Zencey, E. Some brief speculations on the popularity of entropy as metaphor. *Metaphor and Symbol*, **1991**, *6*, 47-56.

[8] Gyarmati, I. *Non-equilibrium thermodynamics*. Springer, Berlin, 1970.

[9] Brody, A. Physical (phenomenological) economics? (A semi-centennial for J. von Neumann and W. Leontief). *Acta Oeconomica*, **1989**, *41*, 257-266.

[10] Ackerman, F. Still dead after all these years: Interpreting the failure of general equilibrium theory. *Journal of Economic Methodology*, **2002**, *9*, 119-139.

[11] Brooks, D.R.; Wiley, E.O. *Evolution as entropy: Toward a unified theory of biology, 2nd ed.* University of Chicago Press, Chicago, Illinois, USA, 1988.
[12] Brooks, D.R.; Wiley, E.O.; Collier, J.D.; Maurer, B.A.; Smith, J.D.H.; E. O. Willey, E.O. Entropy and information in evolving biological systems. *Biology and Philosophy*, **1989**, *4*, 407-432.
[13] Platt, J.R. Social chain reactions. *Bulletin of the Atomic Scientists: Man and his habitat, Part II*, **1961**, *17*, 365-386, available: New York. *The step to man*. John Wiley & Sons. 1966, 39-52.
[14] Prigogine, I. *Introduction to thermodynamics of irreversible processes, 2nd ed.* Wiley, New York, NY, USA 1961.
[15] Prigogine, I. Unity of physical laws and levels of description. In Prigogine, I.; Grene, M. eds. *Interpretations of life and mind: Essays around the problem of reduction*. Humanities Press, New York, NY, USA 1971, 1-13.
[16] Prigogine, I. Order through fluctuation: Self-organization and social system. In Jantsch, E.; Waddington, C. eds. *Consciousness and evolution: Human systems in transition*. Addison Wesley, New York, NY, USA 1976, 93-130.
[17] Prigogine, I. Physics and metaphysics. In Lawrence, J.H.; Gofman, J.W.; Hayes, T.L. Eds. *Advances in biological and medical physics, Vol. 16*. Academic Press, New York, NY, USA 1977, 241-263.
[18] Schieve, W.C.; Allen, P. Eds. *Self-organization and dissipative structures: Applications in the physical and social sciences*. University of Texas Press, Austin, Texas, 1982.
[19] Achermann, G.; De Luca, G.; Simoni, M. An information-theoretic and dissipative systems approach to the study of knowledge diffusion and emerging complexity in innovation systems. In *International conference on computational science*. Springer, Cham, Switzerland, 2020, 252-265.
[20] Andrade, E. Integration of thermodynamic, quantum and hierarchical theories of information in the context of Peircean semiosis--A review. *BioSystems*, **2014**, *120*, 10-20.
[21] Arthur, W.B. Complexity economics: A different framework for economic thought. In Arthur, W.B., ed. *Complexity and the economy*. Oxford University Press, New York, NY, USA 2014, 1-29.
[22] Artigiani, R. Revolution and evolution: Applying Prigogine's dissipative structures model. *Journal of Social and Biological Structures*, **1987**, *10*, 249-264.
[23] Bailey, K.D. Living systems theory and social entropy theory. *Systems Research and Behavioral Science*, **2006**, *23*, 291-300.
[24] Bailey, K.D. Boundary maintenance in living systems theory and social entropy theory. *Systems Research and Behavioral Science*, **2009**, *25*, 587-597.
[25] de Castro, C.; McShea, D.W. Applying the Prigogine view of dissipative systems to the major transitions in evolution. *Paleobiology*, **2022**, 1-18.
[26] Dinga, E. Tanasescu, Social entropy and normative network. *Entropy*, **2020**, *22*, 1051.
[27] Dixon, P.W. On Amit Goswami and Maggie Goswami's quantum creativity: Waking up to our creative potential: Entropy, information theory, and dissipative structures. *Creativity Research Journal*, **2002**, *14*, 439-440.
[28] Giampietro, M. Multi-scale integrated analysis of societal and ecosystem metabolism. In Villamayor-Tomas, S.; Muradian, R., Eds. *The Barcelona School of Ecological Economics and Political Ecology: A Companion in Honour of Joan Martinez-Alier*. Springer International Publishing, Cham, Switzerland, 2023, 109-121.
[29] Haddad, W.M. Thermodynamics: The unique universal science. *Entropy*, **2017**, *19*.
[30] Hidalgo, C. *Why information grows: The evolution of order, from atoms to economies*. Basic Books, New York, NY, USA 2015.
[31] Hodas, N.O.; Lerman, K. The simple rules of social contagion. *Scientific Reports*, **2014**, *4*, 4343.
[32] Laszlo, E. Technology and social change: An approach from nonequilibrium systems theory. *Technological Forecasting & Social Change*, **1986**, *29*, 271-283.
[33] Laszlo, E. Ed. *The new evolutionary paradigm: Keynote volume*. Routledge, London, UK, 2019.
[34] Mitar, M. Bailey's social entropy theory as an explicit theoretical approach for an empirical assessment of security of contemporary societies. *Quality and Quantity*, **2010**, *44*, 941-955.
[35] Mitchell, M. *Complexity: A guided tour*. Oxford University Press, New York, NY, USA 2009.
[36] von Foerster, H. On self-organizing systems and their environments. In *Understanding understanding: Essays on cybernetics and cognition*. Springer, New York, NY, USA 2003, 1-19.
[37] Prigogine, I.; Stengers, I. *La nouvelle alliance: Métamorphose de la science*. Gallimard.
[38] Prigogine, I.; Stengers, I. *Order out of chaos: Man's new dialogue with nature*. Bantam Books, New York, NY, USA 1984.
[39] Prigogine, I. A new rationality? *Mondes en développement*, **1986**, *14*, 19-39.
[40] Scott, J.C. *Seeing like a state: How certain schemes to improve the human condition have failed*. Yale University Press, New Haven, Connecticut, USA, 1998.
[41] Jasanoff, S. Technologies of humility: Citizen participation in governing science. *Minerva*, **2003**, *41*, 223-244.
[42] Stengers, I. The challenge of ontological politics. In de la Cadena, M.; Blaser, M., Eds. *A world of many worlds*. Duke University Press, Durham, North Carolina, USA, 2018, 83-111.

[43] Melin, J.; Cano, S.; Pendrill, L. The role of entropy in construct specification equations (CSE) to improve the validity of memory tests. *Entropy*, **2021**, *23*, 212.
[44] Melin, J.; Cano, S.; Flöel, A.; Göschel, L.; Pendrill, L. The role of entropy in construct specification equations (CSE) to improve the validity of memory tests: Extension to word lists. *Entropy*, **2022**, *24*, 934.
[45] Melin, J.; Pendrill, L.R. The role of construct specification equations (CSE) and entropy in the measurement of memory. In Fisher, W.P. Jr.; Cano, S.J., Eds. *Person-centered outcome metrology*. Springer, Cham, Switzerland, 2023.
[46] Massof, R.W.; Bradley, C. Constructing a latent disease state variable from all relevant clinical examination data. In Fisher, W.P. Jr.; Pendrill, L.R., Eds. *Models, measurement, and metrology extending the SI*. De Gruyter, Berlin, Germany, 2024.
[47] Pendrill, L.R.; Melin, J.; Cano, S.J.; EMPIR NeuroMET 15HLT04 consortium, Metrological references for health care based on entropy. *19th International Congress of Metrology (CIM2019)*, **2019**.
[48] Fisher, W.P. Jr.; Cano, S. Eds. *Person-centered outcome metrology: Principles and applications for high stakes decision making*. Springer, Cham, Switzerland, 2023.
[49] Fisher, W.P. Jr.; Massengill, P.J. *Explanatory models, unit standards, and personalized learning in educational measurement: Selected papers by A. Jackson Stenner*. Springer, Cham, Switzerland, 2023.
[50] Mari, L.; Wilson, M. An introduction to the Rasch measurement approach for metrologists. *Measurement*, **2014**, *51*, 315-327.
[51] Mari, L.; Wilson, M.; Maul, A. *Measurement across the sciences: Developing a shared concept system for measurement, 2nd ed.* Springer, Cham, Switzerland, 2023.
[52] Melin, J.; Cano, S.J.; Flöel, A.; Göschel, L.; Pendrill, L. Metrological advancements in cognitive measurement: A worked example with the NeuroMET memory metric providing more reliability and efficiency. *Measurement: Sensors*, **2023**, *25*, 100658.
[53] Melin, J.; Cano, S.J.; Gillman, A.; Marquis, S.; Flöel, A.; Göschel, L.; Pendrill, L.R. Traceability and comparability through crosswalks with the NeuroMET Memory Metric. *Scientific Reports*, **2023**, *13*, 5179.
[54] Pendrill, L.R. Man as a measurement instrument. *NCSLi Measure: The Journal of Measurement Science*, **2014**, *9*, 22-33.
[55] Pendrill, L.R. Using measurement uncertainty in decision-making and conformity assessment. *Metrologia*, **2014**, *51*, S206-S218.
[56] Pendrill, L.R. *Quality assured measurement: Unification across social and physical sciences*. Springer, Cham, Switzerland, 2019. Springer Series in Measurement Science and Technology.
[57] Pendrill, L.; Fisher, W.P. Jr. Counting and quantification: Comparing psychometric and metrological perspectives on visual perceptions of number. *Measurement*, **2015**, *71*, 46-55.
[58] Andersen, E.B. *Discrete statistical models with social science applications*. North-Holland, Amsterdam, 1980.
[59] Brogden, H.E. The Rasch model, the law of comparative judgment and additive conjoint measurement. *Psychometrika*, **1977**, *42*, 631-634.
[60] Fischer, G.H. On the existence and uniqueness of maximum-likelihood estimates in the Rasch model. *Psychometrika*, **1981**, *46*, 59-77.
[61] Fisher, W.P. Jr.; Wright, B.D., Eds. Applications of probabilistic conjoint measurement. *International Journal of Educational Research*, **1994**, *21*, 557-664.
[62] Narens, L.; Luce, R.D. Measurement: The theory of numerical assignments. *Psychological Bulletin*, **1986**, *99*, 166-180.
[63] Rasch, G. *Probabilistic models for some intelligence and attainment tests*. Danmarks Paedogogiske Institut, Copenhagen, Denmark, 1960.
[64] Rasch, G. On general laws and the meaning of measurement in psychology. In Neyman, J., ed. *Proceedings of the fourth Berkeley symposium on mathematical statistics and probability: Volume IV: Contributions to biology and problems of medicine*. University of California Press, Berkeley, California, 1961, 321-333 [http://www.rasch.org/memo1960.pdf].
[65] Rasch, G. On specific objectivity: An attempt at formalizing the request for generality and validity of scientific statements. *Danish Yearbook of Philosophy*, **1977**, *14*, 58-94.
[66] Wright, B.D. Solving measurement problems with the Rasch model. *Journal of Educational Measurement*, **1977**, *14*, 97-116 [http://www.rasch.org/memo42.htm].
[67] Wright, B.D. Fundamental measurement for outcome evaluation. *Physical Medicine & Rehabilitation State of the Art Reviews*, **1997**, *11*, 261-288.
[68] Pendrill, L.R. Discussion on the definition of the term "unit". In Ulrich, J., ed. *pp. 12-16, in Report of the 24th meeting of the Consultative Committee for Units to the International Committee for Weights and Measures*. Pavillon de Breteuil, Sèvres, France. Bureau International des Poids et Mesures, Consultative Committee for Units (CCU), 2019.
[69] Hutchins, E. Cognitive ecology. *Topics in Cognitive Science*, **2010**, *2*, 705-715.
[70] Hutchins, E. The cultural ecosystem of human cognition. *Philosophical Psychology*, **2014**, *27*, 34-49.
[71] Latour, B. How to talk about the body? The normative dimension of science studies. *Body & Society*, **2004**, *10*, 205-229.

[72] Nersessian, N.J. Engineering concepts: The interplay between concept formation and modeling practices in bioengineering sciences. *Mind, Culture, and Activity*, **2012**, *19*, 222-239.
[73] Overton, W.F. Contexts of meaning: The computational and the embodied mind. In Overton, W.; D. Palermo, D., Eds. *The nature and ontogenesis of meaning*. Lawrence Erlbaum Associates, Inc., Hillsdale, New Jersey, USA, 1994, 1-18.
[74] Overton, W.F. Beyond dichotomy: An embodied active agent for cultural psychology. *Culture & Psychology*, **1997**, *3*, 315-334.
[75] Overton, W.F. Understanding, explanation, and reductionism: Finding a cure for Cartesian anxiety. In Smith, L.; Brown, T., Eds. *Reductionism and the development of knowledge*. Erlbaum, Mahwah, New Jersey, USA, 2002, 29-51.
[76] Overton, W.F. A coherent metatheory for dynamic systems: Relational organicism-contextualism. *Human Development*, **2007**, *50*, 154-159.
[77] Garcia, R. The structure of knowledge and the knowledge of structure. In Beilin, H.; Pufall, P., Eds. *Piaget's theory: Prospects and possibilities*. Lawrence Erlbaum Associates, Inc., Hillsdale, New Jersey, USA, 1992, 21-38.
[78] Overton, W.F. The arrow of time and the cycle of time: Concepts of change, cognition, and embodiment. *Psychological Inquiry*, **1994**, *5*, 215-237.
[79] Akrich, M.; Callon, M.; Latour, B. The key to success in innovation Part I: The art of interessement. *International Journal of Innovation Management*, **2002**, *6*, 187-206 [doi: 10.1142/S1363919602000550].
[80] Akrich, M.; Callon, M.; Latour, B. The key to success in innovation Part II: The art of choosing a good spokesperson. *International Journal of Innovation Management*, **2002**, *6*, 207-225.
[81] Blok, A.; Farias, I.; Roberts, C. Eds. *The Routledge companion to Actor-Network Theory*. Routledge, London, UK, 2020.
[82] Latour, B. *Reassembling the social: An introduction to Actor-Network-Theory*. Oxford University Press, Oxford, UK, 2005.
[83] Latour, B. To modernise or ecologise? That is the question. In Braun, B.; Castree, N., Eds., *Remaking reality: Nature at the millennium*. Routledge, London, UK, 1998, 221-242.
[84] Fisher, W.P. Jr.; Stenner, A.J. Ecologizing vs modernizing in measurement and metrology. *Journal of Physics Conference Series*, **2018**, *1044*,[http://iopscience.iop.org/article/10.1088/1742-6596/1044/1/012025].
[85] Morrison, J.; Fisher, W.P. Jr, Caliper: Measuring success in STEM learning ecosystems. *Measurement: Sensors*, **2021**, *18*, 100327.
[86] Piaget, J. *Play, dreams and imitation in childhood (Vol. 25)*. Routledge, New York, NY, USA 2013.
[87] Overton, W.F. Developmental psychology: Philosophy, concepts, and methodology. *Handbook of Child Psychology*, **1998**, *1*, 107-188.
[88] Overton, W.F., Processes, relations and Relational-Developmental-Systems. In Overton, W.F.; Molenaar, P.C.M., Eds. *Theory and Method. Volume 1 of the Handbook of child psychology and developmental science (7th Ed.)*. Wiley, Hoboken, New Jersey, USA, 2015, 9-62.
[89] Gadamer, H.-G. *Truth and method*. Crossroad, New York, NY, USA 1989.
[90] Commons, M.L.; Bresette, L.M. Illuminating major creative scientific innovators with postformal stages. In Hoare, C., ed. *Handbook of adult development and learning*. Oxford University Press, Oxford, UK, 2006, 255-280.
[91] Commons, M.L.; Ross, S.N.; Bresette, L.M. The connection between postformal thought, stage transition, persistence, and ambition and major scientific innovations. In Artistico, D.; Berry, J.; Black, J.; Cervone, D.; Lee, C.; Orom, H., Eds. *The Oxford handbook of reciprocal adult development and learning*. Oxford University Press, Oxford, UK, 2011, 287-301.
[92] Nersessian, N.J. Child's play. *Philosophy of Science*, **1996**, *63*, 542-546.
[93] Nuzzo, A. Thinking being: Method in Hegel's logic of being. In Houlgate, S.; Bauer, M., Eds. *A Companion to Hegel*. Blackwell, Oxford, UK, 2011, 109-138.
[94] Fischer, K.W. A theory of cognitive development: The control and construction of hierarchies of skills. *Psychological Review*, **1980**, *87*, 477- 531.
[95] Dawson, T.L.; Fischer, K.W.; Stein, Z. Reconsidering qualitative and quantitative research approaches: A cognitive developmental perspective. *New Ideas in Psychology*, **2006**, *24*, 229-239.
[96] Fischer, K.W.; Farrar, M.J. Generalizations about generalization: How a theory of skill development explains both generality and specificity. *International Journal of Psychology*, **1987**, *22*, 643-677.
[97] Barab, S.A.; Plucker, J.A. Smart people or smart contexts? Cognition, ability, and talent development in an age of situated approaches to knowing and learning. *Educational Psychologist*, **2002**, *37*, 165-182.
[98] Shore, D.A. *Launching and leading change initiatives in health care organizations: Managing successful projects (Vol. 213)*. Jossey-Bass, San Francisco, California, USA2014.
[99] Commons, M.L.; Goodheart, E.A. Cultural progress is the result of developmental level of support. *World Futures: The Journal of New Paradigm Research*, **2008**, *64*, 406-415.
[100] Dewey, J. *The public and its problems*. Swallow Press, Ohio University Press, Athens, Ohio, 1954.
[101] Whitehead, A.N. *Science and the modern world*. Macmillan, New York, NY, USA 1925.

[102] Bateson, G. *Steps to an ecology of mind: Collected essays in anthropology, psychiatry, evolution, and epistemology*. University of Chicago Press, Chicago, Illinois, USA, 1972.
[103] Fisher, R.A. Indeterminism and natural selection. *Philosophy of Science*, **1934**, *1*, 99-117.
[104] Odum, H.T.; Cantlon, J.E.; Kornicker, L.S. An organizational hierarchy postulate for the interpretation of species-individual distributions, species entropy, ecosystem evolution, and the meaning of a species-variety index. *Ecology*, **1960**, *41*, 395-399.
[105] Acs, Z.J.; Estrin, S.; Mickiewicz, T.; Szerb, L. Entrepreneurship, institutional economics, and economic growth: An ecosystem perspective. *Small Business Economics*, **2018**, *51*, 501-514.
[106] Latour, B. *Science in action: How to follow scientists and engineers through society*. Harvard University Press, New York, NY, USA 1987.
[107] Mitchell, T. Rethinking economy. *Geoforum*, **2008**, *39*, 1116-1121.
[108] Fisher, W.P. Jr. What the world needs now: A bold plan for new standards. *Standards Engineering*, **2012**, *64*, 1 & 3-5 [http://ssrn.com/abstract=2083975].
[109] Fisher, W.P. Jr. Measure and manage: Intangible assets metric standards for sustainability. In Marques, J.; Dhiman, S.; Holt, S., Eds. *Business administration education: Changes in management and leadership strategies*. Palgrave Macmillan, New York, NY, USA 2012, 43-63.
[110] Fisher, W.P. Jr. Measurement systems, brilliant results, and brilliant processes in healthcare: Untapped potentials of person-centered outcome metrology for cultivating trust. In Fisher, W.P. Jr.; Cano, S., Eds. *Person-centered outcome metrology: Principles and applications for high stakes decision making*. Springer, Cham, Switzerland, 2023, 357-396.
[111] Fisher, W.P. Jr. Separation theorems in econometrics and psychometrics: Rasch, Frisch, two Fishers, and implications for measurement. *Journal of Interdisciplinary Economics*, **2023**, *35*, 29-60.
[112] Lenton, T.M.; Latour, B. Gaia 2.0: Could humans add some level of self-awareness to Earth's self-regulation? *Science*, **2018**, *361*, 1066-1068.
[113] Lerner, R.M.; Overton, W.F. Reduction to absurdity: Why epigenetics invalidates all models involving genetic reduction. *Human Development*, **2017**, *60*, 107-123.
[114] Meloni, M. *Impressionable biologies: From the archaeology of plasticity to the sociology of epigenetics*. Routledge, New York, NY, USA 2019.
[115] Tadelis, S.; Williamson, O. Transaction cost economics. Haas School of Business, University of California, Berkeley, 2010.
[116] Hayek, F.A. The use of knowledge in society. *American Economic Review*, **1945**, *35*, 519-530. (Rpt. in F. A. Hayek, *Individualism and economic order*. University of Chicago Press, Chicago, Illinois, USA. 1948, 77-91.)
[117] Fisher, W.P. Jr., The central theoretical problem of the social sciences. *Rasch Measurement Transactions*, **2014**, *28*,1464-1466.
[118] Prigogine, I. Science, civilization and democracy: Values, systems, structures and affinities. *Futures*, **1986**, *18*, 493-507.
[119] Prigogine, I. *The end of certainty: Time, chaos, and the new laws of nature*. Free Press, New York, NY, USA 1997.
[120] Galison, P. Trading zone: Coordinating action and belief. In Biagioli, M., ed. *The science studies reader*. Routledge, New York, NY, USA 1999, 137-160.
[121] Galison, P. *Image and logic: A material culture of microphysics*. University of Chicago Press, Chicago, Illinois, USA, 1997.
[122] Brier, S. Cybersemiotics: A new foundation for transdisciplinary theory of information, cognition, meaningful communication and the interaction between nature and culture. *Integral Review*, **2013**, *9*, 220-263.
[123] Brier, S. Cybersemiotics and the reasoning powers of the universe: Philosophy of information in a semiotic-systemic transdisciplinary approach. *Green Letters: Studies in Ecocriticism*, **2015**, *19*, 280-292.
[124] Brier, S. Cybersemiotic systemic and semiotical based transdisciplinarity. In Vidales, C.; Brier, S., Eds. *Introduction to cybersemiotics: A transdisciplinary perspective*. Springer, Cham, Switzerland, 2021, 17-31.
[125] Danesi, M. Semiotics as a metalanguage for the sciences. In Bankov, K.; Cobley, P., Eds. *Semiotics and its masters*. DeGruyter, Berlin, 2017, 61-81.
[126] Nöth, W. The semiotics of models. *Sign Systems Studies*, **2018**, *46*, 7-43.
[127] Nöth, W. System, sign, information, and communication in cybersemiotics, systems theory, and Peirce. In Vidales, C.; Brier, S., Eds. *Introduction to cybersemiotics: A transdisciplinary perspective*. Springer, Cham, Switzerland, 2021, 75-95.
[128] Olteanu, A.; Campbell, C.; Feil, S. Naturalizing models: New perspectives in a Peircean key. *Biosemiotics*, **2020**, *13*, 179-197.
[129] Sebeok, T.A. *Signs: An introduction to semiotics*. University of Toronto Press, Toronto, 2001.
[130] Ackermann, J.R. *Data, instruments, and theory: A dialectical approach to understanding science*. Princeton University Press, Princeton, New Jersey, 1985.
[131] Blok, A.; Nakazora, M.; Winthereik, B.R. Infrastructuring environments. *Science as Culture*, **2016**, *25*, 1-22.

[132] Bowker, G.C. How knowledge infrastructures learn. In Harvey, P.; Jensen, C.B.; Morita, A., Eds. *Infrastructures and social complexity: A companion*. Routledge, New York, NY, USA 2016, 391-403.
[133] Bowker, G.C.; Star, S.L. How things (actor-net) work: Classification, magic and the ubiquity of standards. *Philosophia*, **1996**, *25*, 195-220.
[134] Hankins, T.L.; Silverman, R.J. *Instruments and the imagination*. Princeton University Press, Princeton, New Jersey, 1999.
[135] Heelan, P.A., Natural science as a hermeneutic of instrumentation. *Philosophy of Science*, **1983**, *50*, 181-204.
[136] Heelan, P.A. Paradoxes of measurement. *Annals of the New York Academy of Sciences*, **2003**, *988*, 114-127.
[137] Ihde, D. *Instrumental realism: The interface between philosophy of science and philosophy of technology*. Indiana University Press, Bloomington, Indiana, 1991. The Indiana Series in the Philosophy of Technology.
[138] Knorr Cetina, K. Laboratory studies: The cultural approach to the study of science. In Jasanoff, S.; Markle, G.E.; Petersen, J.C.; Pinch, T., Eds. *Handbook of science and technology studies*. Sage Publications, Thousand Oaks, California, 1995, 140-166.
[139] Knorr Cetina, K. *Epistemic cultures: How the sciences make knowledge*. Harvard University Press, Cambridge, Massachusetts, 1999.
[140] Latour, B. Give me a laboratory and I will raise the world. In Knorr-Cetina, K.D.; Mulkay, M., Eds. *Science observed: Perspectives on the social study of science*. Sage Publications, London, England, 1983, 141-170.
[141] Latour, B. Postmodern? No, simply amodern: Steps towards an anthropology of science. *Studies in History and Philosophy of Science*, **1990**, *21*, 145-171.
[142] Latour, B. *We have never been modern*. Harvard University Press, Cambridge, Massachusetts, 1993.
[143] Latour, B. Love your monsters: Why we must care for our technologies as we do our children, *Breakthrough Journal*, **2012**, *2*, Available: https://thebreakthrough.org/journal/issue-2/love-your-monsters.
[144] Rabkin, Y.M. Rediscovering the instrument: Research, industry, and education. In Bud, R.; Cozzens, S.E., Eds. *Invisible connections: Instruments, institutions, and science*. SPIE Optical Engineering Press, Bellingham, Washington, 1992, 57-82.
[145] Rodríguez-Giralt, I.; Marrero-Guillamón, I.; Milstein, D. Reassembling activism, activating assemblages: An introduction. *Social Movement Studies*, **2018**, *17*, 257-268.
[146] Schaffer, S. Late Victorian metrology and its instrumentation: A manufactory of Ohms. In Bud, R.; Cozzens, S.E., Eds. *Invisible connections: Instruments, institutions, and science*. SPIE Optical Engineering Press, Bellingham, WA, 1992, 23-56.
[147] Schaffer, S. Metrology, metrication, and Victorian values. In Lightman, B. ed. *Victorian science in context*. University of Chicago Press, Chicago, Illinois, USA, 1997, 438-474.
[148] Schaffer, S. Modernity and metrology. In Guzzetti, L., Ed. *Science and power: The historical foundations of research policies in Europe*. Office for Official Publications of the European Communities, Luxembourg, 2000, 71-91.
[149] Shapin, S. The invisible technician. *American Scientist*, **1989**, *77*, 554-563.
[150] Shapin, S.; Schaffer, S. *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life*. Princeton University Press, Princeton, New Jersey, USA, 1985.
[151] Vertesi, J.; Ribes, D. *DigitalSTS: A field guide for science & technology studies*. Princeton University Press, Princeton, New Jersey, USA, 2019.
[152] Vonderau, A. Scaling the cloud: Making state and infrastructure in Sweden. *Ethnos Journal of Anthropology*, **2019**, *84*, 698-718.
[153] Guttman, L. The language of science. In Levy, S., ed. *Louis Guttman on theory and methodology: Selected writings*. Dartmouth Publishing Company, Brookfield, VT, 1994, 79-102.
[154] Wright, B.D. A history of social science measurement. *Educational Measurement: Issues and Practice*, **1997**, *16*, 33-45, 52 [http://www.rasch.org/memo62.htm].
[155] Stenner, A.J.; Horabin, I. Three stages of construct definition. *Rasch Measurement Transactions*, **1992**, *6*, 229 [http://www.rasch.org/rmt/rmt63b.htm].
[156] Dawson, T.L. Rethinking educational assessment in light of a strong theory of development. In Mascolo, M.F.; Bidell, T.R., Eds. *Handbook of integrative developmental science: Essays in honor of Kurt W. Fischer*. Routledge, New York, NY, USA 2020, 423-450.
[157] Chaitin, G.J. Randomness and complexity in pure mathematics. *International Journal of Bifurcation and Chaos*, **1994**, *4*, 3-15.
[158] Calude, C.S. Incompleteness, complexity, randomness and beyond. *Minds and Machines*, **2002**, *12*, 503-517.
[159] Calude, C.S. Ed. *Randomness & complexity from Leibniz to Chaitin*. World Scientific, Singapore, 2007.
[160] Chaitin, G.J. Randomness in arithmetic and the decline & fall of reductionism in pure mathematics. *EATCS Bulletin*, **1993**, *50*, 314-328.
[161] Chaitin, G.J. *The limits of mathematics*. Springer-Verlag, London, 2003.

[162] Dewey, J. *The quest for certainty: A study of the relation of knowledge and action*. Perigee Books, G. P. Putnam's Sons, New York, NY, USA 1929.
[163] Kline, M. *Mathematics: The loss of certainty*. Oxford University Press, Oxford, UK, 1980.
[164] Nagel, E.; Newman, J.R. *Gödel's Proof*. New York University Press, New York, NY, USA 1958.
[165] Weinsheimer, J. *Gadamer's hermeneutics: A reading of Truth and Method*. Yale University Press, New Haven, Connecticut, USA, 1985.
[166] Kuhn, T.S. *The structure of scientific revolutions*. University of Chicago Press, Chicago, Illinois, USA, 1970.
[167] Dupre, J. *The disorder of things: Metaphysical foundations of the disunity of science*. Harvard University Press, Cambridge, Massachusetts, 1993.
[168] Galison, P.; Stump, D. eds. *Disunity and contextualism*. Stanford University Press, Palo Alto, California, USA, 1996.
[169] Star, S.L.; Griesemer, J.R. Institutional ecology, 'translations,' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, **1989**, *19*, 387-420.
[170] Woolley, A.W.; Fuchs, E. Collective intelligence in the organization of science. *Organization Science*, **2011**, *22*, 1359-1367.
[171] Cripps, S.; Durrant-Whyte, H. Uncertainty: Nothing is more certain. *Environmetrics*, **2023**, *34*,e2745.
[172] Commons, M.L.; Richards, F.A. Four postformal stages. In Demick, J.; Andreoletti, C., Eds. *Handbook of adult development*. Plenum Press, New York, NY, USA 2002, 199-219.
[173] Commons, M.L.; Richards, F.A.; Kuhn, D. Systematic and metasystematic reasoning: A case for levels of reasoning beyond Piaget's stage of formal operations. *Child Development*, **1982**, *53*, 1058-1069.
[174] Commons, M.L.; Trudeau, E.J.; Stein, S.A.; Richards, F.A.; Krause, S.R. Hierarchical complexity of tasks shows the existence of developmental stages. *Developmental Review*, **1998**, *18*, 237-278.
[175] Berti, M.; Simpson, A.V. The dark side of organizational paradoxes: The dynamics of disempowerment. *Academy of Management Review*, **2021**, *46*, 252-274.
[176] Ross, S.N. A future society functioning at the paradigmatic stage? *World Futures*, **2008**, *64*, 554-562.
[177] Bernstein, W.J. *The birth of plenty: How the prosperity of the modern world was created*. McGraw-Hill, New York, NY, USA 2004.
[178] De Soto, H. *The mystery of capital: Why capitalism triumphs in the West and fails everywhere else*. Basic Books, New York, NY, USA 2000.
[179] Ekins, P. A four-capital model of wealth creation. In Ekins, P.; Max-Neef, M., Eds. *Real-life economics: Understanding wealth creation*. Routledge, London, 1992, 147-155.
[180] Ekins, P.; Dresner, S.; Dahlstrom, K. The four-capital method of sustainable development evaluation. *European Environment*, **2008**, *18*, 63-80.
[181] Fisher, W.P. Jr. Invariance and traceability for measures of human, social, and natural capital: Theory and application. *Measurement*, **2009**, *42*, 1278-1287.
[182] Prigogine, I. Dialogue avec Piaget sur l'irréversible [Dialogue with Piaget concerning the irreversible]. *Archives de Psychologie*, **1982**, *50*, 7-16.
[183] Prigogine, I. Laws of nature and human conduct: Specificities and unifying themes. *Mondes en développement*, **1986**, *14*, 5-8.
[184] Brent, S.B. Prigogine's model for self-organization in nonequilibrium systems: Its relevance for developmental psychology. *Human Development*, **1978**, *21*, 374-387.
[185] Brent, S.B. *Psychological and social structures*. Routledge.
[186] Chapman, M. *Constructive evolution: Origins and development of Piaget's thought*. Cambridge University Press.
[187] Ståhle, P.; Mononen, L.; Tynjälä, P.; Kallio, E.K. Systems thinking and adult cognitive development. In Kallio, E.K., ed. *Development of adult thinking: Interdisciplinary perspectives on cognitive development and adult learning*. Routledge, London, 2020, 191-207.
[188] Prigogine, I.; Allen, P.M. The challenge of complexity. In Schieve, W.C.; Allen, P., Eds. *Self-organization and dissipative structures: Applications in the physical and social sciences*. University of Texas Press, Austin, Texas, 1982, 3-39.
[189] Fisher, R.A. On the mathematical foundations of theoretical statistics. *Philosophical Transactions of the Royal Society of London, A*, **1922**, *222*, 309-368.
[190] Fisher, R.A. Two new properties of mathematical likelihood. *Proceedings of the Royal Society, A*, **1934**, *144*, 285-307.
[191] Duncan, O.D.; Stenbeck, M. Panels and cohorts: Design and model in the study of voting turnout. In Clogg, C.C., ed. *Sociological Methodology 1988*. American Sociological Association, Washington, DC, 1988, 1-35.
[192] Duncan, O.D. What if? *Contemporary Sociology*, **1992**, *21*, 667-668.
[193] Andrich, D. Distinctions between assumptions and requirements in measurement in the social sciences. In Keats, J.A.; Taft, R.; Heath, R.A.; Lovibond, S.H., Eds. *Mathematical and Theoretical Systems:*

Proceedings of the 24th International Congress of Psychology of the International Union of Psychological Science, Vol. 4. Elsevier Science Publishers, North-Holland, 1989, 7-16.
[194] Cohen, J. The earth is round ($p < 0.05$). *American Psychologist*, **1994**, *49*, 997-1003.
[195] Guttman, L. The illogic of statistical inference for cumulative science. *Applied Stochastic Models and Data Analysis*, **1985**, *1*, 3-10.
[196] Meehl, P.E. Theory-testing in psychology and physics: A methodological paradox. *Philosophy of Science*, **1967**, *34*, 103-115.
[197] Michell, J. Measurement scales and statistics: A clash of paradigms. *Psychological Bulletin*, **1986**, *100*, 398-407.
[198] Molenaar, P. A manifesto on psychology as idiographic science: Bringing the person back into scientific psychology, this time forever. *Measurement: Interdisciplinary Research and Perspective*, **2004**, *2*, 201-218.
[199] Rodgers, J.L. The epistemology of mathematical and statistical modeling: A quiet methodological revolution. *American Psychologist*, **2010**, *65*, 1-12.
[200] Rogosa, D. Casual [sic] models do not support scientific conclusions: A comment in support of Freedman. *Journal of Educational Statistics*, **1987**, *12*, 185-195.
[201] Wilson, M.R. Seeking a balance between the statistical and scientific elements in psychometrics. *Psychometrika*, **2013**, *78*, 211-236.
[202] Wright, B.D. Despair and hope for educational measurement. *Contemporary Education Review*, **1984**, 3, 281-288 [http://www.rasch.org/memo41.htm].
[203] Wright, B.D. Fundamental measurement for psychology. In Embretson, S.E.; Hershberger, S.L., Eds. *The new rules of measurement: What every educator and psychologist should know*. Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1999, 65-104 [http://www.rasch.org/memo64.htm].
[204] Guttman, L. Measurement as structural theory. *Psychometrika*, **1971**, *36*, 329-347.
[205] Bich, W. Measurement uncertainty and metrological traceability. In Jeckelmann, B.; Edelmaier, R., Eds. *Metrological infrastructure*. De Gruyter Oldenbourg, Berlin, Germany, 2023, 23-56.
[206] Joint Committee for Guides in Metrology, W.G.1. *Guide to the expression of uncertainty in measurement -- Part 6: Developing and using measurement models*. International Bureau of Weights and Measures--BIPM, Sevres, France, 2020.
[207] Rossi, G. Probability in metrology. In Pavese, F.; Forbes, A.B., Eds. *Data modeling for metrology and testing in measurement science*. Birkhäuser, Boston, Massachusetts, USA, 2009, 31-70.
[208] Rossi, G.B.; Crenna, F. A formal theory of the measurement system. *Measurement*, **2018**, *116*, 644-651.
[209] Morawski, R.Z. An application-oriented mathematical meta-model of measurement. *Measurement*, **2013**, *46*, 3753-3765.
[210] Rasch, G. An individualistic approach to item analysis. In Lazarsfeld, P.F.; Henry, N.W., Eds. *Readings in mathematical social science*. Science Research Associates, Chicago, Illinois, USA, 1966, 89-108.
[211] Luecht, R.M.; Hambleton, R.K. Item response theory: A historical perspective and brief introduction to applications. In Clauser, B.E.; Bunch, M.B., Eds. *The history of educational measurement: Key advancements in theory, policy, and practice*. Routledge.
[212] Andrich, D. Constructing fundamental measurements in social psychology. In Keats, J.A.; Taft, R.; Heath, R.A.; Lovibond, S.H., Eds. *Mathematical and theoretical systems. Proceedings of the 24th International Congress of Psychology of the International Union of Psychological Science, Vol. 4*. North-Holland, Amsterdam, Netherlands, 1989, 17-26.
[213] Embretson, S.E. Item Response Theory models and spurious interaction effects in factorial ANOVA designs. *Applied Psychological Measurement*, **1996**, *20*, 201-212.
[214] Hambleton, R.; Wright, B.D.; Crocker, L.; Masters, G.; van der Linden, W. Hambleton's 9 theses. *Rasch Measurement Transactions*, **1992**, *6*, 215 [http://www.rasch.org/rmt/rmt62.htm].
[215] Lumsden, J. Tests are perfectly reliable. *British Journal of Mathematical and Statistical Psychology*, **1978**, *31*, 19-26.
[216] San Martin, E.; Rolin, J.M. Identification of parametric Rasch-type models. *Journal of Statistical Planning and Inference*, **2013**, *143*, 116-130.
[217] San Martin, E.; Gonzalez, J.; Tuerlinckx, F. On the unidentifiability of the fixed-effects 3 PL model. *Psychometrika*, **2015**, *80*, 450-467.
[218] Verhelst, N.D.; Glas, C.A.W. The one parameter logistic model. In Fischer, G.H.; Molenaar, I.W., Eds. *Rasch models: Foundations recent developments, and applications*. Springer, New York, NY, USA 1995, 215-237.
[219] Linacre, J.M. What is Item Response Theory, IRT? A tentative taxonomy. *Rasch Measurement Transactions*, **2003**, *17*, 926-927.
[220] Hambleton, R.K.; Swaminathan, H.; Rogers, L. *Fundamentals of item response theory*. Sage Publications, Newbury Park, California, 1991.
[221] Shrader-Frechette, K. *Tainted: How philosophy of science can expose bad science*. Oxford University Press, New York, NY, USA 2014.
[222] Kuhn, T.S. *The essential tension: Selected studies in scientific tradition and change*. University of Chicago Press, Chicago, Illinois, USA, Illinois, 1977.

[223] Butterfield, H. *The origins of modern science (revised edition)*. The Free Press, New York, NY, USA 1957.
[224] Kant, I. *Critique of pure reason*, Smith, N.K., trans. St. Martin's Press, New York, NY, USA 1929/1965.
[225] Boumans, M. Paul Ehrenfest and Jan Tinbergen: A case of limited physics transfer. In De Marchi, N., ed. *Non-natural social science: Reflecting on the enterprise of "More Heat than Light"*. Duke University Press, Durham, North Carolina, USA, 1993, 131-156.
[226] Boumans, M. Measurement in economic systems. *Measurement*, **2005**, *38*, 275-284.
[227] Brenner-Golomb, N. R. A. Fisher's philosophical approach to inductive inference. In Keren, G.; Lewis, C., Eds. *A handbook for data analysis in the behavioral sciences: Methodological issues*. Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1993, 283-307.
[228] Wright, B.D. Useful measurement through concurrent equating and one-step (concurrent) item banking. *Rasch Measurement Transactions*, **1988**, *2*, 24 [http://www.rasch.org/rmt/rmt22f.htm].
[229] Fisher, W.P. Jr. Contextualizing sustainable development metric standards: Imagining new entrepreneurial possibilities. *Sustainability*, **2020**, *12*, 1-22.
[230] Wilson, M.; Fisher, W.P. Jr. Eds. *Psychological and social measurement: The career and contributions of Benjamin D. Wright*, Cain, M.G.; Rossi, G.B.; Tesai, J.; van Veghel, M.; Jhang, K.-Y., Eds. Springer Nature, Cham, Switzerland, Switzerland, 2017. Springer Series in Measurement Science and Technology.
[231] Perline, R.; Wright, B.D.; Wainer, H. The Rasch model as additive conjoint measurement. *Applied Psychological Measurement*, **1979**, *3*, 237-255.
[232] Newby, V.A.; Conner, G.R.; Grant, C.P.; Bunderson, C.V. The Rasch model and additive conjoint measurement. *Journal of Applied Measurement*, **2009**, *10*, 348-354.
[233] Peabody, M.R.; Muckle, T.J.; Meng, Y. Applying a mixture Rasch model-based approach to standard setting. *Educational Measurement: Issues and Practice*, **2023**, *42*, 5-12.
[234] Smith, R.M.; Julian, E.; Lunz, M.; Stahl, J.; Schulz, M.; Wright, B.D. Applications of conjoint measurement in admission and professional certification programs. *International Journal of Educational Research*, **1994**, *21*, 653-664.
[235] Black, P.; Wilson, M.; Yao, S. Road maps for learning: A guide to the navigation of learning progressions. *Measurement: Interdisciplinary Research and Perspectives*, **2011**, *9*, 1-52.
[236] Duckor, B.; Holmberg, C. Exploring how to model formative assessment trajectories of posing-pausing-probing practices: Toward a teacher learning progressions framework for the study of novice teachers. *Journal of Educational Measurement*, **2019**, *56*, 836-890.
[237] Duckor, B.; Holmberg, C. Examining conceptual frameworks for understanding teacher learning in the domain of formative assessment. In *International Encyclopedia of Education*, Volume 5. Elsevier, 2023, 581-595.
[238] Duckor, B.; Holmberg, C. *Feedback for continuous improvement in the classroom: New perspectives, practices, and possibilities*. Corwin, 2023.
[239] Wilson, M.R. Cognitive diagnosis using item response models. *Zeitschrift für Psychologie/Journal of Psychology (Special Issue: Current Issues in Competence Modeling and Assessment)*, **2008**, *216*, 74-88.
[240] Wilson, M.R. Measuring progressions: Assessment structures underlying a learning progression. *Journal of Research in Science Teaching*, **2009**, *46*, 716-730.
[241] Wilson, M.R. Making measurement important for education: The crucial role of classroom assessment. *Educational Measurement: Issues and Practice*, **2018**, *37*, 5-20.
[242] Commons, M.L. What are the relationships between four notions of stage change? *Behavioral Development Bulletin*, **2014**, *19*, 15-21.
[243] Commons, M.L.; Goodheart, E.A.; Pekker, A.; Dawson-Tunik, T.L.; Adams, K.M. Using Rasch scaled stage scores to validate orders of hierarchical complexity of balance beam task sequences. *Journal of Applied Measurement*, **2008**, *9*, 182-199.
[244] Commons, M.L.; Miller, P.M.; Ramakrishnan, S.; Giri, S. Employee management using behavioral development theory. *Behavioral Development*, **2018**, *23*, 22-33.
[245] Dawson, T.L.; Goodheart, E.A.; Draney, K.; Wilson, M.; Commons, M.L. Concrete, abstract, formal, and systematic operations as observed in a "Piagetian" balance-beam task. In Garner, M.; Engelhard, G. Jr.; Fisher, W.P. Jr.; Wilson, M., Eds. *Advances in Rasch Measurement, Vol. 1*. JAM Press, Maple Grove, MN, USA 2010, 572-590.
[246] Dawson-Tunik, T.L.; Commons, M.; Wilson, M.; Fischer, K. The shape of development. *The European Journal of Developmental Psychology*, **2005**, *2*, 163-196.
[247] Draney, K.; Wilson, M. Application of the polytomous Saltus model to stage-like proportional reasoning data. In Van der Ark, L.A.; Croon, M.A.; Sijtsma, K., Eds. *New developments in categorical data analysis for the social and behavioral sciences*. Psychology Press, 207-226.
[248] Draney, K.; Wilson, M. Application of the Saltus model to stage-like data: Some applications and current developments. In von Davier, M., ed. *Multivariate and mixture distribution Rasch models*. Springer, New York, NY, USA 2006.
[249] Mueller, U.; Overton, W.F. Thinking about thinking - thinking about measurement: A Rasch analysis of recursive thinking. *Journal of Applied Measurement*, **2010**, *11*, 78-90.

[250] Wilson, M.R. Saltus: A psychometric model of discontinuity in cognitive development. *Psychological Bulletin*, **1989**, *105*, 276-289.
[251] Barney, M. Transdisciplinary measurement through AI: Hybrid metrology and psychometrics powered by Large Language Models. In Fisher, W.P. Jr.; Pendrill, L. eds. *Models, measurement, and metrology extending the SI*. De Gruyter, Berlin, Germany, 2024.
[252] Barney, M.; Fisher, W.P. Jr. Adaptive measurement and assessment. *Annual Review of Organizational Psychology and Organizational Behavior*, **2016**, *3*, 469-490.
[253] Lunz, M.E.; Bergstrom, B.A.; Gershon, R.C. Computer adaptive testing. *International Journal of Educational Research*, **1994**, *21*, 623-634.
[254] Cano, S.; Pendrill, L.; Melin, J.; Fisher, W.P. Jr. Towards consensus measurement standards for patient-centered outcomes. *Measurement*, **2019**, *141*, 62-69.
[255] Fisher, W.P. Jr.; Stenner, A.J. Theory-based metrological traceability in education: A reading measurement network. *Measurement*, **2016**, *92*, 489-496.
[256] Masters, G.N. Special issue: Programme for International Student Assessment (PISA). *Journal of Applied Measurement*, **2007**, *8*, 235-335.
[257] Quaglia, M.; Pendrill, L.; Melin, J.; Cano, S.; 18HLT09 NeuroMET2 Consortium *Publishable Summary for 18HLT09 NeuroMET2: Metrology and innovation for early diagnosis and accurate stratification of patients with neurodegenerative diseases*. EMPIR NeuroMET. EURAMET, Teddington, Middlesex, UK, 2019-2022, 5 pp.
[258] Stenner, A.J. The Lexile Framework: A common metric for matching readers and texts. *California School Library Journal*, **2001**, *25*, 41-42.
[259] Aldrich, J. Autonomy. *Oxford Economic Papers*, **1989**, *41*, 15-34.
[260] Koopmans, T.C.; Reiersøl, O. The identification of structural characteristics. *The Annals of Mathematical Statistics*, **1950**, *XXI*, 165-181.
[261] Andrich, D.; Douglas, G.A. A binomial latent trait model for the study of Likert-style attitude questionnaires. *British Journal of Mathematical and Statistical Psychology*, **1978**, *31*, 84-98.
[262] Andrich, D. A rating formulation for ordered response categories. *Psychometrika*, **1978**, *43*, 561-573.
[263] Andrich, D. Sufficiency and conditional estimation of person parameters in the polytomous Rasch model. *Psychometrika*, **2010**, *75*, 292-308.
[264] Wright, B.D.; Masters, G.N. *Rating scale analysis*. MESA Press, Chicago, Illinois, USA, 1982.
[265] Graßhoff, U.; Holling, H.; Schwabe, R. D-optimal design for the Rasch counts model with multiple binary predictors. *British Journal of Mathematical and Statistical Psychology*, **2020**, *73*, 541-555.
[266] Meredith, W.M. *The Poisson distribution and Poisson process in psychometric theory*. Educational Testing Service, Princeton, New Jersey, USA, 1968, 81 pp.
[267] Rasch, G. The Poisson process as a model for a diversity of behavioral phenomena. Washington, DC. International Congress of Psychology.
[268] Andersen, E.B. Asymptotic properties of conditional maximum likelihood estimators. *Journal of the Royal Statistical Society*, **1970**, *30*, 283-301.
[269] Andersen, E.B. Sufficient statistics and latent trait models. *Psychometrika*, **1977**, *42*, 69-81.
[270] Barndorff-Nielsen, O. *Exponential families and conditioning*. Aarhus Universite, Denmark, 1973.
[271] Barndorff-Nielsen, O. *Information and exponential families in statistical theory*. John Wiley and Sons, New York, NY, USA 1978.
[272] Bradley, E.L. The equivalence of maximum likelihood and weighted least squares estimates in the exponential family. *Journal of the American Statistical Association*, **1973**, *68*, 199-200.
[273] Charnes, A.; Frome, E.L.; Yu, P.L. The equivalence of generalized least squares and maximum likelihood estimates in the exponential family. *Journal of the American Statistical Association*, **1976**, *71*, 169-171.
[274] Daum, F. The Fisher-Darmois-Koopman-Pitman theorem for random processes. Athens, Greece. 1986 25th IEEE Conference on Decision and Control.
[275] Fraser, D.A.S. On sufficiency and the exponential family. *Journal of the Royal Statistical Society: Series B (Methodological)*, **1963**, *25*, 115-123.
[276] Habermann, S. Maximum likelihood estimates in exponential response models. *The Annals of Statistics*, **1977**, *5*, 815-841.
[277] Koopman, B.O. On distributions admitting a sufficient statistic. *Transactions of the American Mathematical Society*, **1936**, *39*, 399-409.
[278] Linacre, J.M. *A user's guide to WINSTEPS Rasch-Model computer program, v. 5.6.2*. Winsteps.com, Beaverton, Oregon, USA, 2023.
[279] Gottlieb, G. *Individual development and evolution: The genesis of novel behavior*. Oxford University Press, Oxford, UK, 1992.
[280] Cole, M. Cultural mechanisms of cognitive development. In Amsel, E.; Renninger, K.A., Eds. *Change and development: Issues of theory, method, and application*. Lawrence Erlbaum, Mahwah, New Jersey, USA, 1997, 245-263.
[281] Overton, W.F. A new paradigm for developmental science: Relationism and relational-developmental systems. *Applied Developmental Science*, **2013**, *17*, 94-107.

[282] Wright, B.D.; Stone, M.H. *Best Test Design*. MESA Press, Chicago, Illinois, USA, 1979.
[283] Cano, S.; Pendrill, L.; Barbic, S.; Fisher, W.P. Jr. Patient-centred outcome metrology for healthcare decision-making. *Journal of Physics: Conference Series*, **2018**, *1044*,012057.
[284] Quaglia, M.; Pendrill, L.; Melin, J.; Cano, S.; 15HLT04 NeuroMET Consortium *Innovative measurements for improved diagnosis and management of neurodegenerative diseases*. EMPIR NeuroMET. EURAMET, Teddington, Middlesex, UK, 2016-2019, 36 pp.
[285] Petrosky, T.; Prigogine, I. Laws and events: The dynamical basis of self-organization. *Canadian Journal of Physics*, **1990**, *68*, 670-682.
[286] Bohm, D. A suggested interpretation of the quantum theory in terms of "hidden" variables. I. *Physical Review*, **1952**, *85*, 166-179.
[287] Bohm, D. A suggested interpretation of the quantum theory in terms of "hidden" variables. II. *Physical Review*, **1952**, *85*, 180-193.
[288] Bohm, D. *Wholeness and the implicate order*. Routledge & Kegan Paul, London, England, 1980.
[289] Bohm, D.; Hiley, B.J. Measurement understood through the quantum potential approach. *Foundations of Physics*, **1984**, *14*, 255-274.
[290] Bohm, D.; Hiley, B.J.; Kaloyerou, P.N. An ontological basis for the quantum theory. *Physics Reports*, **1987**, *144*, 321-375.
[291] Cowan, C.W.; Tumulka, R. Epistemology of wave function collapse in quantum physics. *The British Journal for the Philosophy of Science*, **2016**, *67*, 405-434.
[292] de Broglie, L.; Rosenfeld, L. Physics and metaphysics. *Nature*, **1958**, *181*, 1814-1814.
[293] Ellinor, L. Bohm’s journey to dialogue: A look at its roots. In Banathy, B. Jenlink, ed. *Dialogue as a means of collective communication*. Springer, Boston, Massachusetts, USA, 2005, 255-276.
[294] Esfeld, M.; Lazarovici, D.; Hubert, M.; Dürr, D. The ontology of Bohmian mechanics. *The British Journal for the Philosophy of Science*, **2014**, *65*, 773-796.
[295] Goldstein, S. Quantum theory without observers-Part one. *Physics Today*, **1998**, *51*, 42-47.
[296] Goldstein, S. Quantum theory without observers-Part two. *Physics Today*, **1998**, *51*, 38-42.
[297] le Breton, P. Scholarly heroism: A transdisciplinary perspective on David Bohm’s transformative scholarship and intellectual exile. *Journal of Humanistic Psychology*, **2018**, *58*, 415-430.
[298] Lovejoy, D. Objectivity, causality, and ideology in modern physics. *Science & Society*, **1999**, *63*, 433-468.
[299] Matarese, V. *The metaphysics of Bohmian mechanics: A comprehensive guide to the different interpretations of Bohmian ontology*, Esfeld, M.; Hartmann, S.; Newen, A., Eds. De Gruyter. Epistemic studies, 51.
[300] Walleczek, J.; Grössing, G.; Pylkkänen, P.; Hiley, B. Emergent quantum mechanics: David Bohm centennial perspectives. *Entropy*, **2019**, *21*, 113.
[301] Wheeler, J.A. The universe as a home for man. *American Scientist*, **1974**, *62*, 683-691.
[302] Wheeler, J.A. The participatory universe. *Science*, **1981**, *81*, 5.
[303] Wheeler, J.A. World as system self-synthesized by quantum networking. *IBM Journal of Research and Development*, **1988**, *32*, 4-15.
[304] Wheeler, J.A. Information, physics, quantum: The search for links. In *Feynman and computation: Exploring the limits of computers*. CRC Press, 309-336.
[305] Meijer, D.K. The universe as a cyclic organized information system: John Wheeler’s world revisited. *NeuroQuantology*, **2015**, *13*, 57-78.
[306] Jaeger, G. On Wheeler’s quantum circuit. In *The quantum-like revolution: A festschrift for Andrei Khrennikov*. Springer International Publishing, Cham, Switzerland, 2023, 25-59.
[307] Duncan, O.D. *Notes on social measurement: Historical and critical*. Russell Sage Foundation, New York, NY, USA 1984.
[308] Fisher, W.P. Jr. Stochastic resonance and Rasch measurement. *Rasch Measurement Transactions*, **1992**, *5*, 186-187 [http://www.rasch.org/rmt/rmt54k.htm].
[309] Fisher, W.P. Jr. Bringing human, social, and natural capital to life: Practical consequences and opportunities. *Journal of Applied Measurement*, **2011**, *12*, 49-66.
[310] Fisher, W.P. Jr. A practical approach to modeling complex adaptive flows in psychology and social science. *Procedia Computer Science*, **2017**, *114*, 165-174.
[311] Fisher, W.P. Jr.; Wilson, M. Building a productive trading zone in educational assessment research and practice. *Pensamiento Educativo: Revista de Investigacion Educacional Latinoamericana*, **2015**, *52*, 55-78.
[312] Crisanti, A.; Falcioni, M.; Paladin, G.; Vulpiani, A. Stochastic resonance in deterministic chaotic systems. *Journal of Physics A: Mathematical and General*, **1994**, *27*,L597.
[313] Petrosky, T.; Prigogine, I. Poincaré resonances and the extension of classical dynamics. *Chaos, Solitons & Fractals*, **1996**, *7*, 441-497.
[314] Prigogine, I.; Rice, S.A. Eds. *Resonances, instability, and irreversibility*, Petrosky, T.; Prigogine, I. eds. John Wiley & Sons, New York, NY, USA 2009. Resonances, instability, and irreversibility: The Liouville space extension of quantum mechanics, 99.

[315] Guttman, L. The basis for scalogram analysis. In Stouffer, S.A.; Guttman, L.; Suchman, E.A.; Lazarsfeld, P.F.; Star, S.A.; Clausen, J.A., Eds. *Measurement and prediction (Studies in social psychology in World War II. volume 4)*. Wiley, New York, NY, USA 1950, 60-90.
[316] Loevinger, J. The attenuation paradox in test theory. *Psychological Bulletin*, **1954**, *51*, 493-504.
[317] Engelhard, G. Jr. What is the attenuation paradox? *Rasch Measurement Transactions*, **1993**, *6*, 257 [http://www.rasch.org/rmt/rmt64.htm].
[318] Masters, G.N. Measurement models for ordered response categories. In Langeheine, R.; Rost, J., Eds. *Latent trait and latent class models*. Plenum Press, Institute for Science Education at the University of Kiel, 1988, 11-30.
[319] Lord, F.M. *Some perspectives on 'The attenuation paradox in test theory'*. ETS, Princeton, New Jersey, USA, 1954, 15 pp.
[320] Lord, F.M. *Applications of item response theory to practical testing problems*. Lawrence Erlbaum, Hillsdale, New Jersey, 1980.
[321] Fisher, W.P. Jr. IRT and confusion about Rasch measurement. *Rasch Measurement Transactions*, **2010**, *24*, 1288 [http://www.rasch.org/rmt/rmt242.pdf].
[322] Adams, R.J.; Wilson, M. ; Wang, W.-C. The Multidimensional Random Coefficients Multinomial Logit Model. *Applied Psychological Measurement*, **1997**, *21*, 1-23.
[323] Adams, R.J.; Wilson, M.; Wu, M. Multilevel item response models: An approach to errors in variables regression. *Journal of Educational and Behavioral Statistics*, **1997**, *22*, 47-76.
[324] Allen, D.D.; Wilson, M. Introducing multidimensional item response modeling in health behavior and health education research. *Health Education Research*, **2006**, *21*, 73-i84.
[325] Beretvas, N.; Kamata, A. Part II. Multi-level measurement Rasch models. In Smith, E.V. Jr. ; Smith, R.M., eds., *Rasch measurement: Advanced and specialized applications* . JAM Press, Maple Grove, MN, (Guest editors) 2007,291-470.
[326] Fischer, G.H. The linear logistic test model as an instrument in educational research. *Acta Psychologica*, **1973**, *37*, 359-374.
[327] Linacre, J.M.; Engelhard, G.; Tatum, D.S.; Myford, C.M. Measurement with judges: Many-faceted conjoint measurement. *International Journal of Educational Research*, **1994**, *21*, 569-577.
[328] von Davier, M., Ed., *Multivariate and mixture distribution Rasch models* . Springer, New York, 2006.
[329] Wilson, M.; Gochyyev, P. Having your cake and eating it too: Multiple dimensions and a composite. *Measurement* , **2020**, *151*.
[330] Andrich, D. A latent trait model for items with response dependencies: Implications for test construction and analysis. In Embretson, S., ed. *Test design: Contributions from psychology, education and psychometrics*. Academic Press, New York, NY, USA 1985, 245-273.
[331] Arminger, G.; Clogg, C.C.; Cheng, T. Regression analysis of multivariate binary response variables using Rasch-type models and finite-mixture methods. *Sociological Methodology*, **2000**, *30*, 1-26.
[332] Eid, M.; Rauber, M. Detecting measurement invariance in organizational surveys. *European Journal of Psychological Assessment*, **2000**, *16*, 20-30.
[333] Haladyna, T.M. Context-dependent item sets. *Educational Measurement*, **1992**, *11*, 21-25.
[334] Hoskens, M.; De Boeck, P. A parametric model for local dependence among test items. *Psychological Methods*, **1997**, *2*, 261-277.
[335] Wilson, M.; Adams, R. Rasch models for item bundles. *Psychometrika*, **1995**, *60*, 181-198.
[336] Wilson, M.; Hoskens, M. The rater bundle model. *Journal of Educational and Behavioral Statistics*, **2001**, *26*, 283-306.
[337] Hendriks, J.; Fyfe, S.; Styles, I.; Skinner, R.; Merriman, G. Scale construction utilising the Rasch unidimensional measurement model: A measurement of adolescent attitudes towards abortion. *Australasian Medical Journal*, **2012**, *5*, 251-261.
[338] Adams, R.J.; Wu, M.; Wilson, M. The Rasch rating model and the disordered threshold controversy. *Educational and Psychological Measurement*, **2012**, *72*, 547-573 [DOI: 10.1177/0013164411432166].
[339] Andrich, D. An expanded derivation of the threshold structure of the polytomous Rasch model that dispels any 'threshold disorder controversy'. *Educational and Psychological Measurement*, **2013**, *73*, 78-124 [DOI: 10.1177/0013164412450877].
[340] Linacre, J.M. Investigating rating scale category utility. *Journal of Outcome Measurement*, **1999**, *3*, 103-122.
[341] Luo, G. The relationship between the rating scale and partial credit models and the implication of disordered thresholds of the Rasch models for polytomous responses. *Journal of Applied Measurement*, **2005**, *6*, 443-55.
[342] Wright, B.D.; Linacre, J.M. Combining and splitting categories. *Rasch Measurement Transactions*, **1992**, *6*, 233-5 [http://www.rasch.org/rmt/rmt63f.htm].
[343] Andrich, D. Models for measurement: Precision and the non-dichotomization of graded responses. *Psychometrika*, **1995**, *60*, 7-26.
[344] Andrich, D.; Marais, I. *A course in Rasch measurement theory: Measuring in the educational, social, and health sciences*. Springer, Cham, Switzerland, Switzerland, 2019.

[345] Andrich, D.; Wright, B.D. Rasch sensitivity and Thurstone insensitivity to graded responses. *Rasch Measurement Transactions*, **1994**, *8*, 382 [http://www.rasch.org/rmt/rmt83m.htm].
[346] Samejima, F. Estimation of latent ability using a response pattern of graded scores. *Psychornetrika Monograph*, **1969**, *17*.
[347] Andrich, D.; Pedler, P. A law of ordinal random error: The Rasch measurement model and random error distributions of ordinal assessments. *Measurement*, **2019**, *131*, 771-781.
[348] Andrich, D.; Surla, D. Equating measuring instruments in the social sciences: Applying measurement principles of the natural sciences. In Fisher, W.P. Jr.; Cano, S., Eds. *Person-centred outcome metrology: Principles and applications for high stakes decision making (Springer Series in Measurement Science & Technology)*. Springer, Cham, Switzerland, 2023, 195-226.
[349] Masters, G.N. Common-person equating with the Rasch model. *Applied Psychological Measurement*, **1985**, *9*, 73-82.
[350] Wolfe, E.W. Understanding Rasch measurement: Equating and item banking with the Rasch model. *Journal of Applied Measurement*, **2000**, *1*, 409-434.
[351] Lord, F.M. The standard error of equipercentile equating. *Journal of Educational Statistics*, **1982**, *7*, 165-174.
[352] Prigogine, I. Time, structure and fluctuations. *Science*, **1978**, *201*, 777-785.
[353] Pattee, H.H. Universal principles of measurement and language functions in evolving systems. In Casti, J.L.; Karlqvist, A. eds. *Complexity, language, and life: Mathematical approaches*. Springer Verlag, Berlin, 1985, 268-281.
[354] Velozo, C.A.; Kielhofner, G.; Lai, J.S. The use of Rasch analysis to produce scale-free measurement of functional ability. *American Journal of Occupational Therapy*, **1999**, *53*, 83-90.
[355] Vass, J. On the Geometry of IFS Fractals and its Applications. [Ph.D. thesis] *diss*. University of Waterloo, Ontario, Canada, Applied Mathematics, 2013.
[356] Peirce, C.S. *The essential Peirce: Selected philosophical writings, volume I (1867-1893)*, Houser, N.; Kloesel, C., Eds. Indiana University Press, Bloomington, 1992.
[357] Sebeok, T.A. In what sense is language a 'primary modeling system'. In Heyvaert, F.J.; Steurs, F., Eds. *World behind words: Essays in honour of Prof. Dr. F. G. Droste on the occasion of his sixtieth birthday*. University of Leuven Press, Leuven, Belgium, 1989, 25-36.
[358] Sebeok, T.A.; Danesi, M. *The forms of meaning: Modeling systems theory and semiotic analysis*. Mouton de Gruyter, Berlin, 2000.
[359] Harvey, P.; Jensen, C.B.; Morita, A. *Infrastructures and social complexity: A companion*. Taylor & Francis.
[360] Lenoir, T. *Inscribing science: Scientific texts and the materiality of communication*. Stanford University Press, Stanford, California, 1998.
[361] Nersessian, N.J. Model-based reasoning in distributed cognitive systems. *Philosophy of Science*, **2006**, *73*, 699-709.
[362] Nersessian, N.J.; Kurz-Milcke, E.; Newstetter, W.C.; Davies, J. Research laboratories as evolving distributed cognitive systems. *Proceedings of the Annual Meeting of the Cognitive Science Society*, **2003**, *25*, 857-862.
[363] Confrey, J.; Shah, M.; Toutkoushian, E. Validation of a learning trajectory-based diagnostic mathematics assessment system as a trading zone. *Frontiers in Education: Assessment, Testing and Applied Measurement*, **2021**, *6*.
[364] Fisher, W.P. Jr. The mathematical metaphysics of measurement and metrology: Towards meaningful quantification in the human sciences. In Morales, A., ed. *Renascent pragmatism: Studies in law and social science*. Ashgate Publishing Co., Brookfield, VT, USA, 2003, 118-153.
[365] Fisher, W.P. Jr. Mathematics, measurement, metaphor, metaphysics: Parts I & II. *Theory & Psychology*, **2003**, *13*, 753-828.
[366] Fisher, W.P. Jr. Meaning and method in the social sciences. *Human Studies: A Journal for Philosophy and the Social Sciences*, **2004**, *27*, 429-454.
[367] Fisher, W.P. Jr. How "deterministic chaos" defines natural laws applicable to both nature and culture. In Durakbasa, N.; Gençyilmaz, M.G., Eds., *Lecture Notes in Mechanical Engineering: Selected papers from ISPR2023, October 5-7, Turkiye*. Springer Verlag, Berlin, 2023.
[368] Lehrer, R. A learning progression emerges in a trading zone of professional community and identity. *WISDOMe Monographs*, **2013**, *3*, 173-186.
[369] Commons, M.L.; Gane-McCalla, R.; Barker, C.D.; Li, E.Y. The model of hierarchical complexity as a measurement system. *Behavioral Development Bulletin*, **2014**, *19*, 9-14.
[370] Jeon, M.; Draney, K.; Wilson, M. A general Saltus LLTM-R for cognitive assessments. In Millsap, R.E.; Bolt, D.M.; van der Ark, L.A.; Wang, W.-C., Eds. *Quantitative Psychology Research. Springer Proceedings in Mathematics & Statistics*. Springer International Publishing, Berlin, 2015. The 78th Annual Meeting of the Psychometric Society, 89, 73-90.
[371] Falmagne, J.-C.; Doignon, J.-P. Stochastic evolution of rationality. *Theory and Decision*, **1997**, *43*, 107-138.

[372] Mislevy, R.J.; & Wilson, M. Marginal maximum likelihood estimation for a psychometric model of discontinuous development. *Psychometrika*, **1996**, *61*, 41-71.
[373] Commons, M.L. Introduction: Attaining a new stage. *Journal of Adult Development*, **2002**, *9*, 155-157.
[374] Ireland, V.; Statsenko, L. Managing complex projects and systems: A literature synthesis. *Australian Journal of Multi-Disciplinary Engineering*, **2020**, *16*, 93-110.
[375] Shannon, C.E. A mathematical theory of communication. In Shannon, C.E.; Weaver, W., Eds. *The mathematical theory of communication*. University of Illinois Press, Urbana, IL, 1949, 29-125.
[376] Layzer, D. The arrow of time. *Scientific American*, **1975**, *233*, 56-69.
[377] Bowman, J.P.; Targowski, A.S., Modeling the communication process: The map is not the territory. *The Journal of Business Communication*, **1987**, *24*, 21-34.
[378] Yuan, X. A symbolic interactionist model of interpreter-facilitated communication-Key communication issues in face-to-face interpreting. *Frontiers in Communication*, **2022**, *7*, 1000849.
[379] Weaver, W. Recent contributions to the mathematical theory of communication. In Shannon, C.E.; Weaver, W., Eds. *The mathematical theory of communication*. University of Illinois Press, Urbana, IL, 1949, 1-28.
[380] Ross, S.N. Fractal transition steps to fractal stages: The dynamics of evolution II. *World Futures: The Journal of New Paradigm Research*, **2008**, *64*, 361-374.
[381] Ross, S.N. Fractal model of nonlinear hierarchical complexity: Measuring transition dynamics as fractals of themselves. *Behavioral Development Bulletin*, **2014**, *19*, 28-.
[382] Badia, X.; Prieto, L.; Roset, M.; Díez-Pírez, A.; Herdman, M. Development of a short osteoporosis quality of life questionnaire by equating items from two existing instruments. *Journal of Clinical Epidemiology*, **2002**, *55*, 32-40.
[383] Dawson, T.L. A comparison of three developmental stage scoring systems. *Journal of Applied Measurement*, **2002**, *3*, 146-89.
[384] Dawson, T.L. New tools, new insights: Kohlberg's moral reasoning stages revisited. *International Journal of Behavioral Development*, **2002**, *26*, 154-66.
[385] Dawson, T.L. A stage is a stage is a stage: A direct comparison of two scoring systems. *Journal of Genetic Psychology*, **2003**, *164*, 335-364.
[386] Dawson, T.L. Assessing intellectual development: Three approaches, one sequence. *Journal of Adult Development*, **2004**, *11*, 71-85.
[387] Fisher, W.P. Jr.; Harvey, R.F.; Kilgore, K.M. New developments in functional assessment: Probabilistic models for gold standards. *NeuroRehabilitation*, **1995**, *5*, 3-25.
[388] Fisher, W.P. Jr.; Harvey, R.F.; Taylor, P.; Kilgore, K.M.; Kelly, C.K. Rehabits: A common language of functional assessment. *Archives of Physical Medicine and Rehabilitation*, **1995**, *76*, 113-122.
[389] Fisher, W.P. Jr.; Eubanks, R.L.; Marier, R.L. Equating the MOS SF36 and the LSU HSI physical functioning scales. *Journal of Outcome Measurement*, **1997**, *1*, 329-362.
[390] Smith, R.M.; Taylor, P. Equating rehabilitation outcome scales: Developing common metrics. *Journal of Applied Measurement*, **2004**, *5*, 229-242.
[391] Bateson, G. Number is different from quantity. *CoEvolution Quarterly*, **1978**, *17*, 44-46 [Reprinted from pp. 53-58 in Bateson, G. (1979). Mind and Nature: A Necessary Unity. New York: E. P. Dutton.].
[392] Fisher, W.P. Jr. Bateson and Wright on number and quantity: How to not separate thinking from its relational context. *Symmetry*, **2021**, *13*.
[393] Wright, B.D. Measuring and counting. *Rasch Measurement Transactions*, **1994**, *8*, 371 [http://www.rasch.org/rmt/rmt83c.htm].
[394] Alker, H.R. A typology of ecological fallacies. In Dogan, M.; Rokkan, S., Eds. *Quantitative ecological analysis in the social sciences*. MIT Press, Cambridge, Massachusetts, 1969, 69-86.
[395] Cash, D.W.; Adger, W.N.; Berkes, F.; Garden, P.; Lebel, L.; Olsson, P.; ..; Young, O. Scale and cross-scale dynamics: Governance and information in a multilevel world. *Ecology and Society*, **2006**, *11*.
[396] Hayman, J.; Rayder, N.; Stenner, A.J.; Madey, D.L. On aggregation, generalization, and utility in educational evaluation. *Educational Evaluation and Policy Analysis*, **1979**, *1*, 31-39.
[397] Kiser, L.L.; Ostrom, E. The three worlds of action: A metatheoretical synthesis of institutional approaches. In Ostrom, E., ed. *Strategies of political inquiry*. Sage, Beverly Hills, 1982, 179-222.
[398] Paul, A.; Lang, J.W.; Baumgartner, R.J. A multilevel approach for assessing business strategies on climate change. *Journal of Cleaner Production*, **2017**, *160*, 50-70.
[399] Rousseau, D.M. Issues of level in organizational research: Multi-level and cross-level perspectives. *Research in Organizational Behavior*, **1985**, *7*, 1-37.
[400] Fisher, W.P. Jr. A nondualist social ethic: Fusing subject and object horizons in measurement. *TMQ--Techniques, Methodologies, and Quality*, **2019**, *10*, 21-40.
[401] Fisher, W.P. Jr.; Pendrill, L.; Lips da Cruz, A.; Felin, A. Why metrology? Fair dealing and efficient markets for the United Nations' Sustainable Development Goals. *Journal of Physics: Conference Series*, **2019**, *1379*.
[402] Fisher, W.P. Jr.; Wilson, M. The BEAR Assessment System Software as a platform for developing and applying UN SDG metrics. *Journal of Physics Conference Series*, **2019**, *1379*.

[403] Fisher, W.P. Jr.; Melin, J.; Möller, C. *Metrology for climate-neutral cities*. RISE Research Institutes of Sweden AB. RISE, Gothenburg, Sweden, 2021, 79 pp.
[404] Fisher, W.P. Jr.; Melin, J.; Möller, C. A preliminary report on metrology for climate-neutral cities. *Acta IMEKO*, **2024**, in press.
[405] Star, S.L.; Ruhleder, K. Steps toward an ecology of infrastructure: Design and access for large information spaces. *Information Systems Research*, **1996**, *7*, 111-134.
[406] Ostrom, E. *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press, Cambridge, UK, 2015. 1990.
[407] Dewey, J. Democracy in education. *The Elementary School Teacher*, **1903**, *4*, 193-204.
[408] Bunderson, C.V.; Newby, V.A. The relationships among design experiments, invariant measurement scales, and domain theories. *Journal of Applied Measurement*, **2009**, *10*, 117-137.
[409] De Boeck, P.; Wilson, M. Eds. *Explanatory item response models: A generalized linear and nonlinear approach*. Springer-Verlag, New York, NY, USA 2004. Statistics for Social and Behavioral Sciences.
[410] Embretson, S.E. *Measuring psychological constructs: Advances in model-based approaches*. American Psychological Association, Washington, DC, 2010.
[411] Graßhoff, U.; Holling, H.; Schwabe, R. Optimal designs for linear logistic test models. In Giovagnoli, A.; Atkinson, A.C.; Torsney, B.; May, C., Eds. *MODa9 -- Advances in Model-Oriented Design and Analysis: Contributions to statistics*. Physica-Verlag HD, Heidelberg, Germany, 2010, 97-104.
[412] Green, K.E.; Kluever, R.C. Components of item difficulty of Raven's Matrices. *Journal of General Psychology*, **1992**, *119*, 189-199.
[413] Green, K.E.; Smith, R.M. A comparison of two methods of decomposing item difficulties. *Journal of Educational Statistics*, **1987**, *12*, 369-381.
[414] Morell, L.; Collier, T.; Black, P.; Wilson, M. A construct-modeling approach to develop a learning progression of how students understand the structure of matter. *Journal of Research in Science Teaching*, **2017**, *54*, 1024-1048.
[415] Pandarova, I.; Schmidt, T.; Hartig, J.; Boubekki, A.; Jones, R.D.; Brefeld, U. Predicting the difficulty of exercise items for dynamic difficulty adaptation in adaptive language tutoring. *International Journal of Artificial Intelligence in Education*, **2019**, *29*, 342-367.
[416] Smith, R.M. Item component equating. In Wilson, M., ed. *Objective measurement: Theory into practice, Vol. 3*. Ablex Publishing Co., Norwood, New Jersey, 1996, 289-308.
[417] Sonnleitner, P. Using the LLTM to evaluate an item-generating system for reading comprehension. *Psychology Science Quarterly*, **2008**, *50*, 345-362.
[418] Stenner, A.J.; Smith, M. III; Burdick, D.S. Toward a theory of construct definition. *Journal of Educational Measurement*, **1983**, *20*, 305-316.
[419] Stenner, A.J.; Fisher, W.P. Jr.; Stone, M.H.; Burdick, D.S. Causal Rasch models. *Frontiers in Psychology: Quantitative Psychology and Measurement*, **2013**, *4*, 1-14.
[420] Chan, T.L.; Perlmutter, M.S.; Andrews, M.; Sunness, J.S.; Goldstein, J.E.; Massof, R.W.; Low Vision Research Network (LOVRNET) Study Group, Equating visual function scales to facilitate reporting of Medicare functional g-code severity/complexity modifiers for low-vision patients. *Archives of Physical Medicine and Rehabilitation*, **2015**, *96*, 1859-1865.
[421] Hobart, J.C.; Cano, S.J.; Zajicek, J.P.; Thompson, A.J. Rating scales as outcome measures for clinical trials in neurology: Problems, solutions, and recommendations. *Lancet Neurology*, **2007**, *6*, 1094-1105.
[422] Cano, S.; Klassen, A.F.; Scott, A.; Thoma, A.; Feeny, D.; Pusic, A. Health outcome and economic measurement in breast cancer surgery: Challenges and opportunities. *Expert Review of Pharmacoeconomics & Outcomes Research*, **2010**, *10*, 583-594.
[423] Fisher, W.P. Jr.; Oon, E.P.-T.; Benson, S. Rethinking the role of educational assessment in classroom communities: How can design thinking address the problems of coherence and complexity? *Educational Design Research*, **2021**, *5*, 1-33.
[424] Draney, K.; Wilson, M. Selecting cut scores with a composite of item types: The construct mapping procedure. *Journal of Applied Measurement*, **2011**, *12*, 298-309.
[425] Wyse, A.E. Construct maps as a foundation for standard setting. *Measurement: Interdisciplinary Research and Perspectives*, **2013**, *11*, 139-170.
[426] Chien, T.W.; Chang, Y.; Wen, K.S.; Uen, Y.H. Using graphical representations to enhance the quality-of-care for colorectal cancer patients. *European Journal of Cancer Care*, **2018**, *27*,e12591.
[427] Mead, R.J. The ISR: Intelligent Student Reports. *Journal of Applied Measurement*, **2009**, *10*, 208-224.
[428] Wright, B.D.; Mead, R.; Bell, S.R. *BICAL: Calibrating items with the Rasch model*. University of Chicago, Illinois, USA, Statistical Laboratory, Department of Education, Chicago, Illinois, USA, 1980, 170 pp.
[429] Hertz, T.; Schlüter, M. The SES-framework as boundary object to address theory orientation in social-ecological system research: The SES-TheOr approach. *Ecological Economics*, **2015**, *116*, 12-24.
[430] Karasti, H. Infrastructuring in participatory design. *Proceedings of the 13th Participatory Design Conference: Research Papers*, **2014**, *1*, 141-150.

[431] Karasti, H.; Millerand, F.; Hine, C.M.; Bowker, G.C. Knowledge infrastructures: Intro to Part I. *Science & Technology Studies*, **2016**, *29*, 2-12.
[432] Halsema, A. The subject of critique: Ricoeur in dialogue with feminist philosophers. *Etudes Ricoeuriennes/Ricoeur Studies*, **2013**, *4*, 21-39.
[433] Ricoeur, P. The critique of subjectivity and cogito in the philosophy of Heidegger. In Frings, M.S., ed. *Heidegger and the quest for truth*. Quadrangle Books, Chicago, Illinois, USA, 1968, 62-75.
[434] Bloom, B.S. The hands and feet of genius: Automaticity. *Educational Leadership*, **1986**, *43*, 70-77.
[435] Cooper, S.; Hebert, M.; Goodrich, J. M.; Leiva, S.; Lin, X.; Peng, P.; Nelson, J. R. Effects of automaticity training on reading performance: A meta-analysis. *Journal of Behavioral Education*, **2022**, 1-30.
[436] Kahneman, D. *Thinking fast and slow*. Farrar, Straus and Giroux, New York, NY, USA 2011.
[437] Rose, T. *Collective illusion: Conformity, complicity, and the science of why we make bad decisions*. Hachette, New York, NY, USA 2022.
[438] Nadler, S.; Shapiro, L. *When bad thinking happens to good people: How philosophy can save us from ourselves*. Princeton University Press, Princeton, New Jersey, USA, 2021.
[439] Stengers, I. *Another science is possible: A manifesto for slow science.* Polity Press, Cambridge, UK, 2018.
[440] Hayek, F.A. *Individualism and economic order*. University of Chicago Press, Chicago, Illinois, USA, 1948.
[441] Whitehead, A.N. *An introduction to mathematics*. Henry Holt and Co., New York, NY, USA 1911.
[442] Ihde, D. *Bodies in technology*. University of Minnesota Press, Minneapolis, Minnesota, USA, 2002.
[443] Overton, W.F. Embodiment from a relational perspective. In Overton, W.F.; Muller, U.; Newman, J.L., Eds. *Developmental perspective on embodiment and consciousness*. Erlbaum, Mahwah, New Jersey, USA, 2008, 1-18.
[444] Fisher, C.M.; Demir-Caliskan, O.; Yingying Hua, M.; A. Cronin, M. Trying not to try: The paradox of intentionality in jazz improvisation and its implications for organizational scholarship. In Bednarek, R.; Pina e Cunha, M.; Schad, J.; Smith, W.K., Eds. *Research in the Sociology of Organizations*, Volume 73b *Interdisciplinary Dialogues on Organizational Paradox: Investigating Social Structures and Human Expression, Part B*. Emerald Publishing Limited, Bingley, 2021, 123-137.
[445] Abram, D. *The spell of the sensuous: Perception and language in a more-than-human world*. Vintage Books, New York, NY, USA 1996.
[446] Stengers, I. *The invention of modern science*, Smith, D.W., trans. University of Minnesota Press, Minneapolis, Minnesota, USA, 2000. Theory out of bounds, 19.
[447] de Solla Price, D.J. Of sealing wax and string. In *Little science, big science--and beyond*. Columbia University Press, New York, NY, USA 1986, 237-253.
[448] Babich, B.E. Material hermeneutics and Heelan's philosophy of technoscience. *AI & Society*, **2020**, 1-12.
[449] Ihde, D. The historical and ontological priority of technology over science. In *Existential technics*. State University of New York Press, Albany, New York, NY, USA 1983, 25-46.
[450] Foxon, T. Bounded rationality and hierarchical complexity: Two paths from Simon to ecological and evolutionary economics. *Complexity and Ecological Economics*, **2006**, *3*, 361-368.
[451] Kahneman, D. Maps of bounded rationality: Psychology for behavioral economics. *American Economic Review*, **2003**, *93*, 1449-1475.
[452] Wittgenstein, L. *Tractatus logico-philosophicus*. Harcourt Brace, London, UK, 1922.
[453] Martland, T.R. On "The limits of my language mean the limits of my world". *The Review of Metaphysics*, **1975**, *29*, 19-26.
[454] Mach, E. *The science of mechanics: A critical and historical account of its development*, McCormack, T.J., trans. The Open Court Publishing Co., Chicago, Illinois, USA, 1919.
[455] Banks, E. The philosophical roots of Ernst Mach's economy of thought. *Synthese*, **2004**, *139*, 23-53.
[456] Franck, G. The scientific economy of attention: A novel approach to the collective rationality of science. *Scientometrics*, **2002**, *55*, 3-26.
[457] Franck, G. The economy of attention. *Journal of Sociology*, **2019**, *55*, 8-19.
[458] Heidegger, M. *What is called thinking?* Gray, J.G., trans. Harper & Row, New York, NY, USA 1968.
[459] North, D.C. *Structure and change in economic history*. W. W. Norton & Co., New York, NY, USA 1981.
[460] Wittgenstein, L. 1953 *Philosophical investigations*, Anscombe, G.E.M., trans. Macmillan, New York, NY, USA 1958.
[461] Pastor-Satorras, R.; Castellano, C.; Van Mieghem, P.; Vespignani, A. Epidemic processes in complex networks. *Reviews of Modern Physics*, **2015**, *87*, 925.
[462] Pentland, A. *Social physics: How good ideas spread-the lessons from a new science*. Penguin, London, UK, 2014.
[463] Diener, P. The evolution of dysfunction. *Culture*, **1982**, *2*, 43-51.
[464] Moore, R. *Niels Bohr: The man and the scientist*. Hodder & Stoughton, London, 1967.
[465] Sahlins, M. *The new science of the enchanted universe: An anthropology of most of humanity*. Princeton University Press, Princeton, New Jersey, USA, 2022.
[466] Kauffmann, S. *At home in the universe: The search for laws of self-organization and complexity*. Oxford University Press, New York, NY, USA 1996.

[467] Ehrenfest-Afanassjewa, T. Zur Axiomatisierung des Zweiten Hauptsatzes der Thermodynamik [On the axiomatization of the second law of thermodynamics]. *Zeitschrift für Physik*, **1925**, *33*, 933-946.
[468] Ehrenfest-Afanassjewa, T. *Relevia: Een nieuw economisch systeem, een orde, waarin ik zelf ook graag zou willen leven*. [*Relevia: A new economic system, an order in which I myself would like to live.*] Boucher, The Hague, 1946.
[469] Prigogine, I.; Defay, R. *Thermodynamique chimique*. Dunod, Paris, 1944.